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**Yilmaz et al.**

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(54) **DEVICE STRUCTURE AND METHODS OF MAKING HIGH DENSITY MOSFETS FOR LOAD SWITCH AND DC-DC APPLICATIONS**

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This patent is subject to a terminal disclaimer.

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**Related U.S. Application Data**

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**H01L 29/66** (2006.01)  
**H01L 29/78** (2006.01)

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(52) **U.S. Cl.**  
CPC ..... **H01L 29/7813** (2013.01); **H01L 27/0251** (2013.01); **H01L 29/0619** (2013.01);  
(Continued)

(58) **Field of Classification Search**  
CPC ..... H01L 29/76; H01L 21/76; H01L 29/00; H01L 31/11; H01L 27/095; H01L 31/062; H01L 31/113; H01L 29/78  
USPC ..... 257/133–137, 329, 334, 280, 341, 471, 257/332, 139, E21.159, E27.06, E21.41, 257/E21.158, E21.419, E29.26, E21.54, 257/E29.262, E21.409; 438/270, 258, 589, 438/211, 257

See application file for complete search history.

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*Primary Examiner* — Jessica Stultz

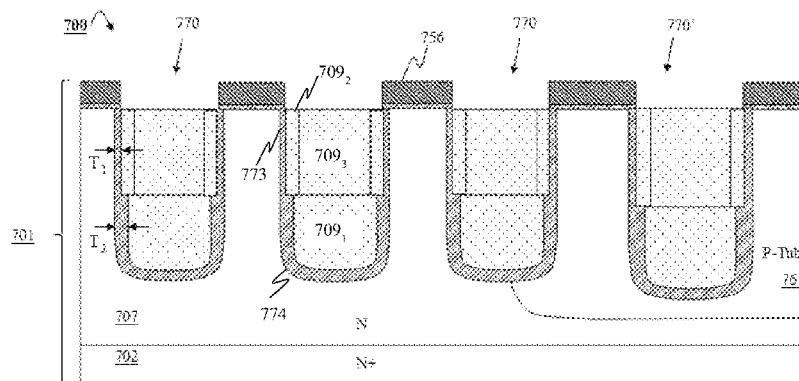
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(57) **ABSTRACT**

Aspects of the present disclosure describe a high density trench-based power. The active devices may have a two-step gate oxide. A lower portion may have a thickness that is larger than the thickness of an upper portion of the gate oxide. A lightly doped sub-body layer may be formed below a body region between two or more adjacent active device structures of the plurality. The sub-body layer extends from a depth of the upper portion of the gate oxide to a depth of the lower portion of the gate oxide. It is emphasized that this abstract is provided to comply with rules requiring an abstract that will allow a searcher or other reader to quickly ascertain the subject matter of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

**10 Claims, 25 Drawing Sheets**



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- (52) **U.S. Cl.**
- CPC ..... *H01L29/0696* (2013.01); *H01L 29/086* (2013.01); *H01L 29/401* (2013.01); *H01L 29/41766* (2013.01); *H01L 29/4236* (2013.01); *H01L 29/42368* (2013.01); *H01L 29/66719* (2013.01); *H01L 29/66727* (2013.01); *H01L 29/66734* (2013.01); *H01L 29/7808* (2013.01); *H01L 29/7811* (2013.01); *H01L 29/7827* (2013.01); *H01L 29/0856* (2013.01); *H01L 29/0865* (2013.01); *H01L 29/0869* (2013.01); *H01L 29/1095* (2013.01); *H01L 29/456* (2013.01); *H01L 29/6656* (2013.01)
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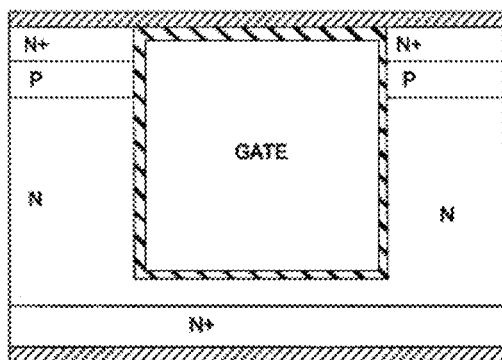


FIG. 1A (Prior Art)

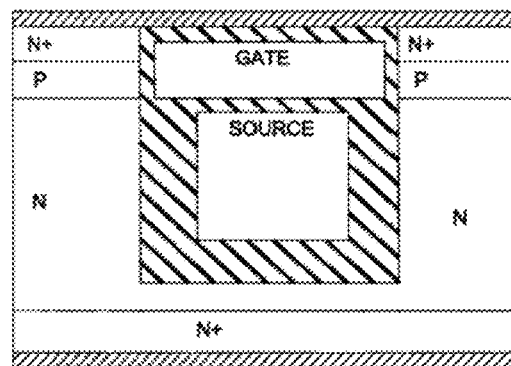


FIG. 1B (Prior Art)

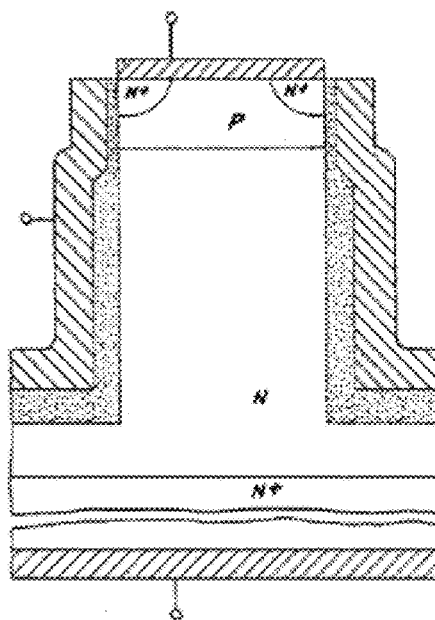


FIG. 1C (Prior Art)

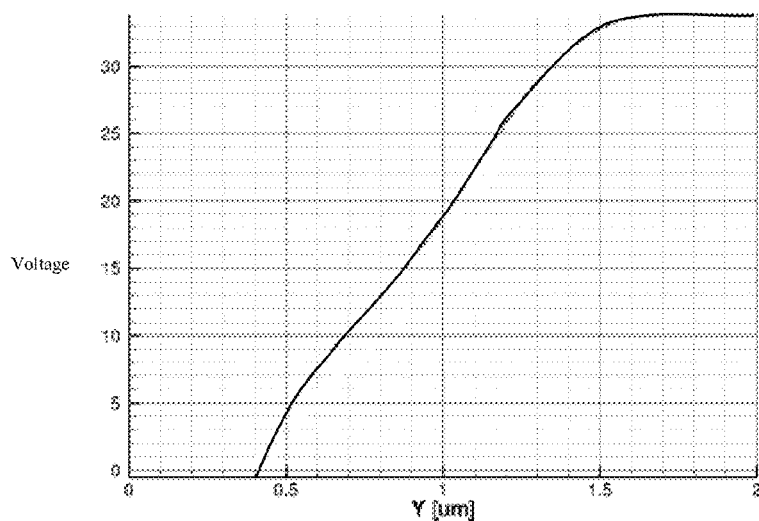


FIG. 2B

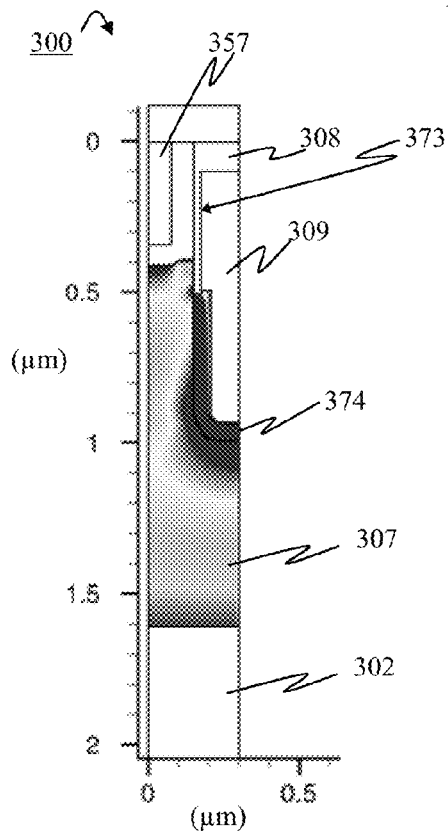


FIG. 2A

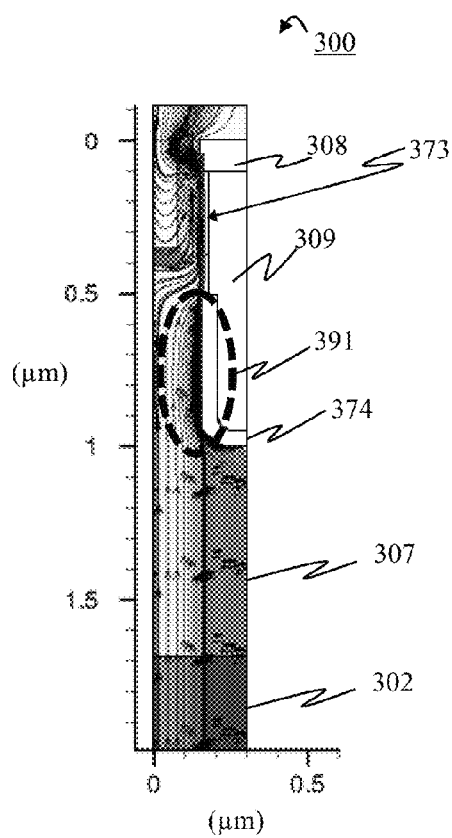


FIG. 2C

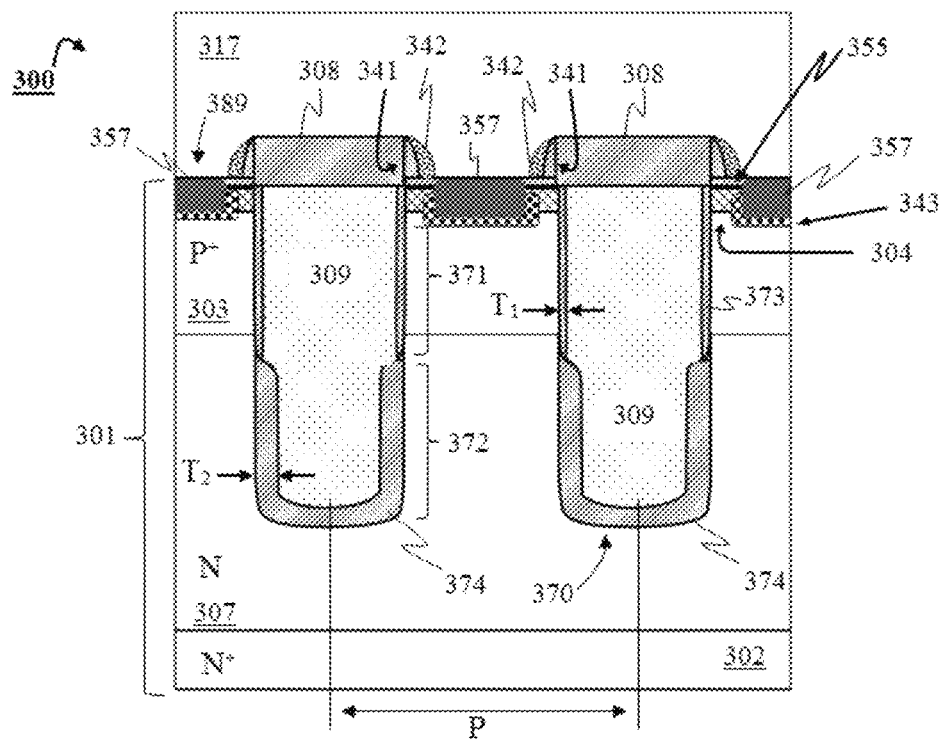


FIG. 3A

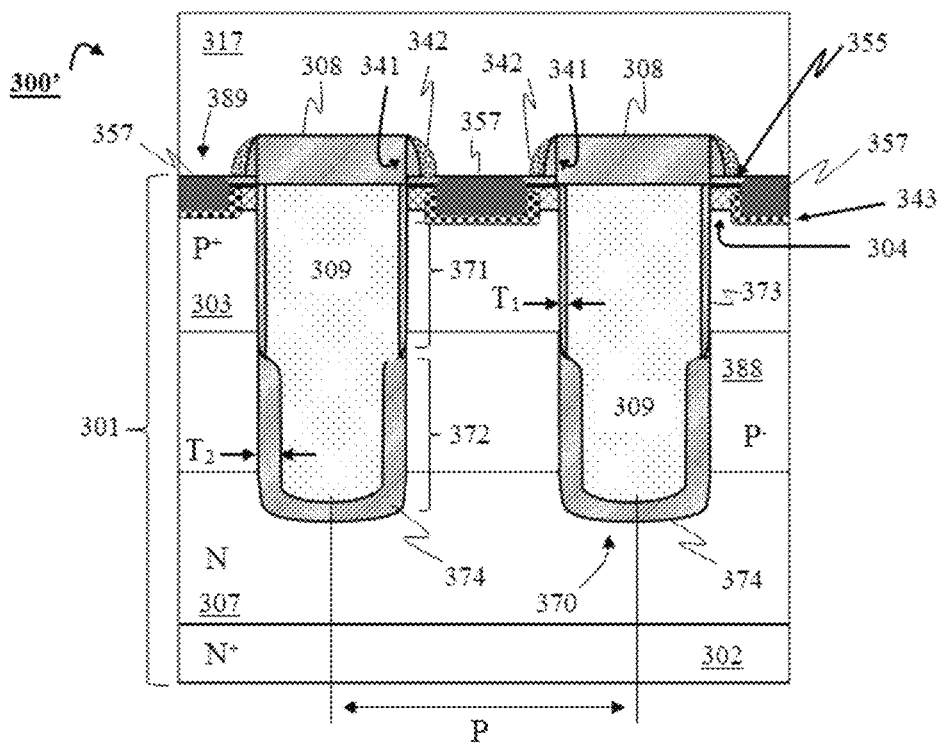


FIG. 3B

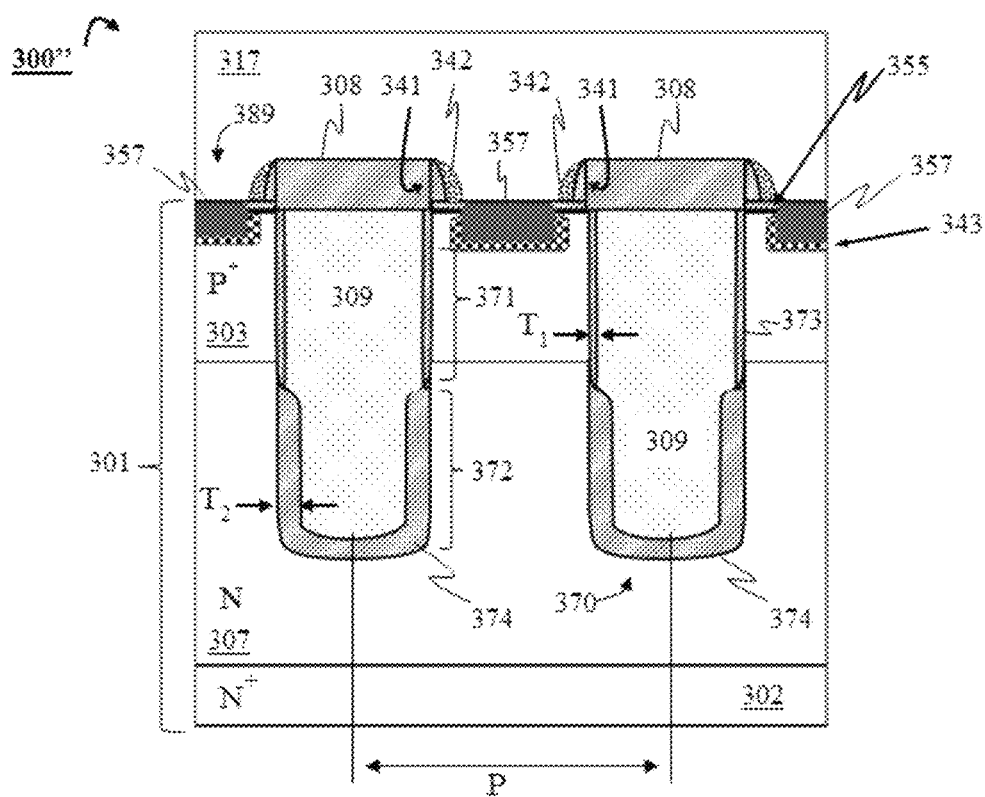


FIG. 3C

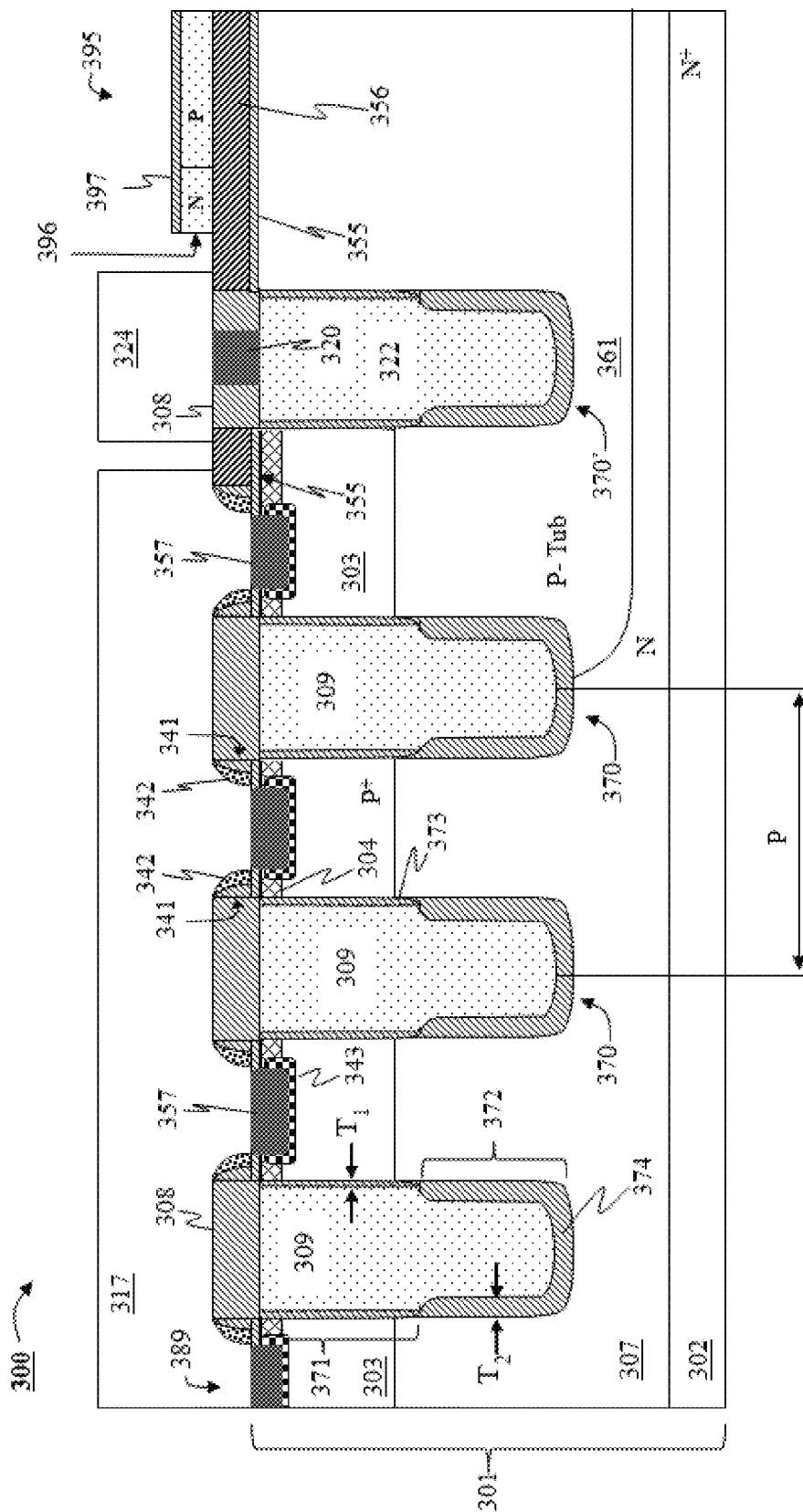
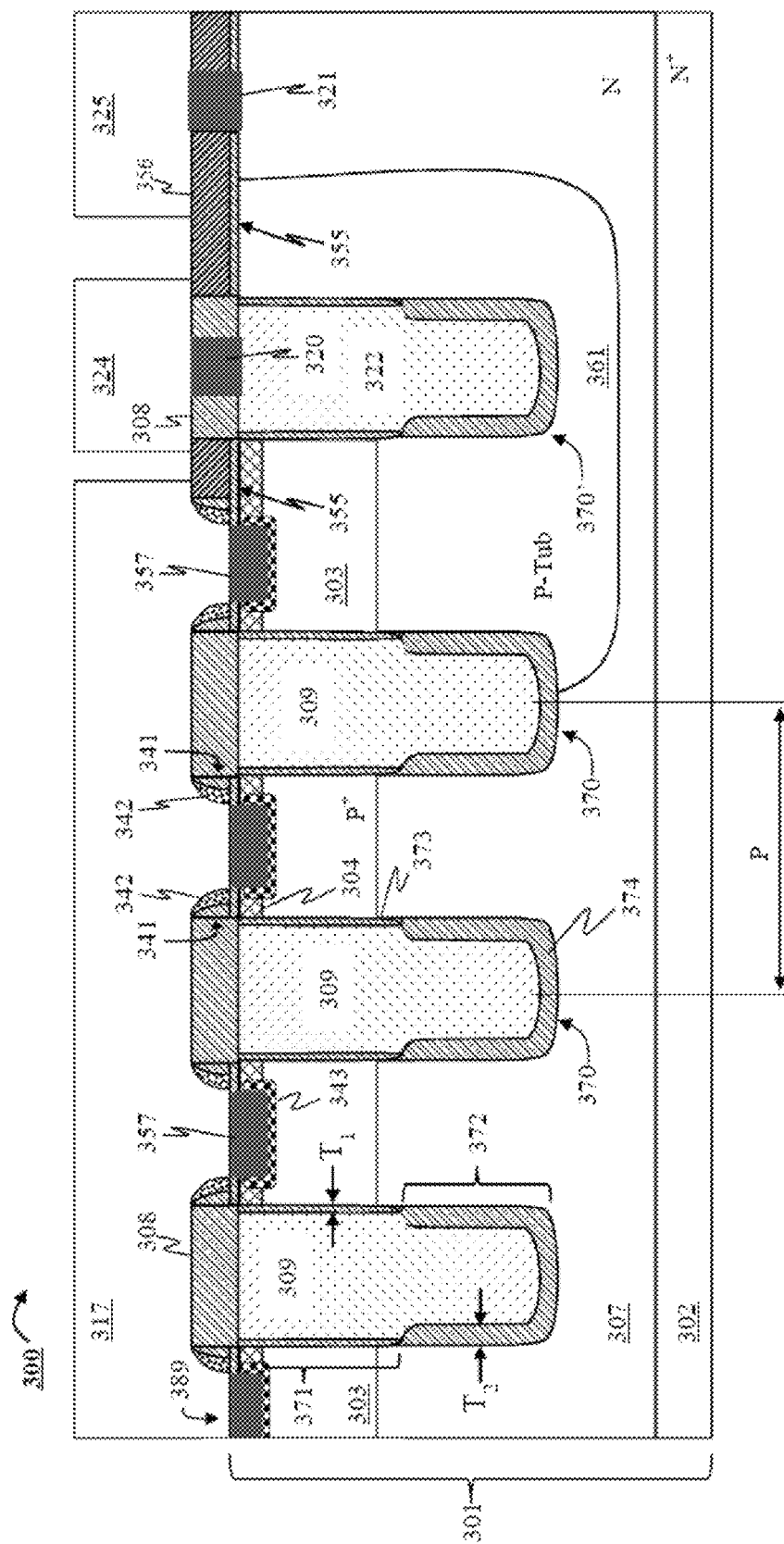


FIG. 3D





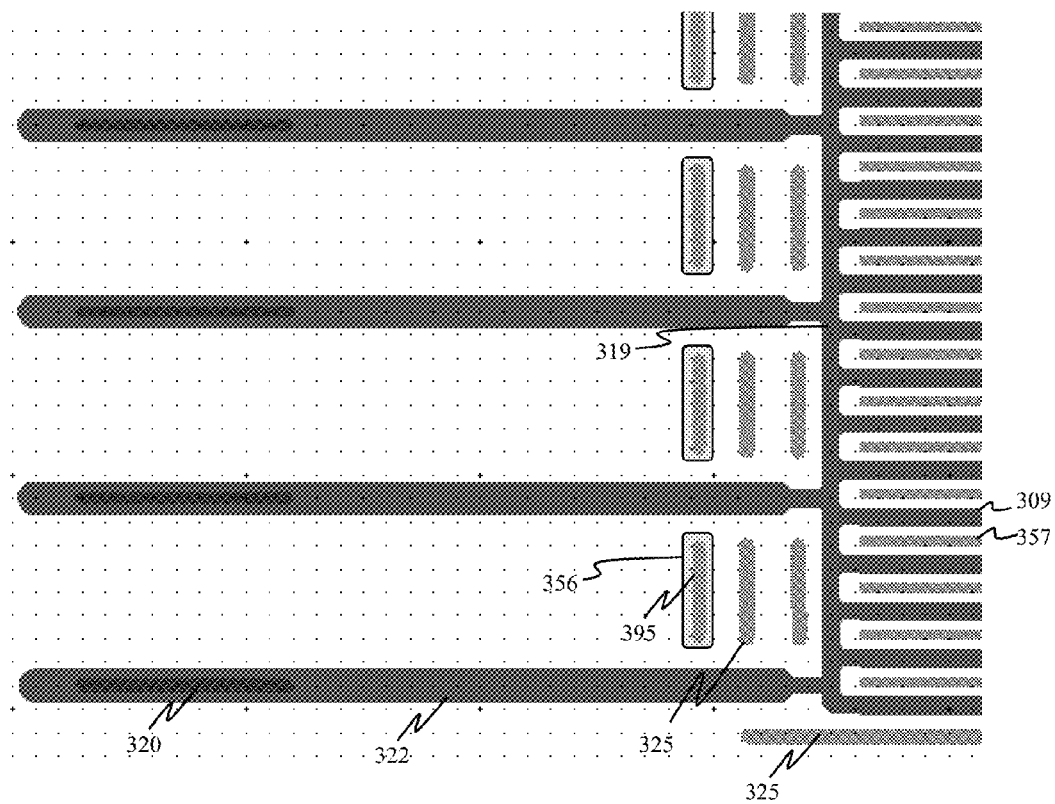


FIG. 4



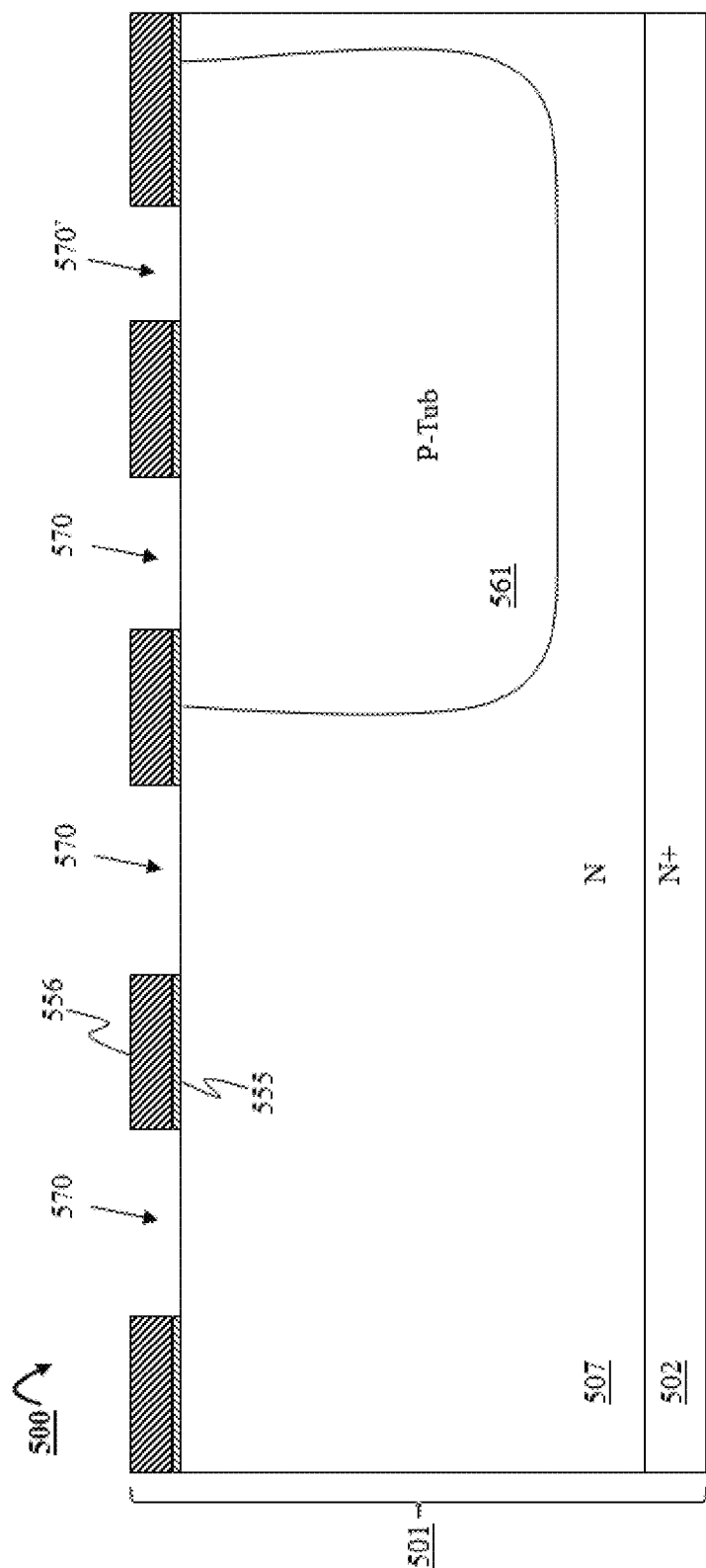
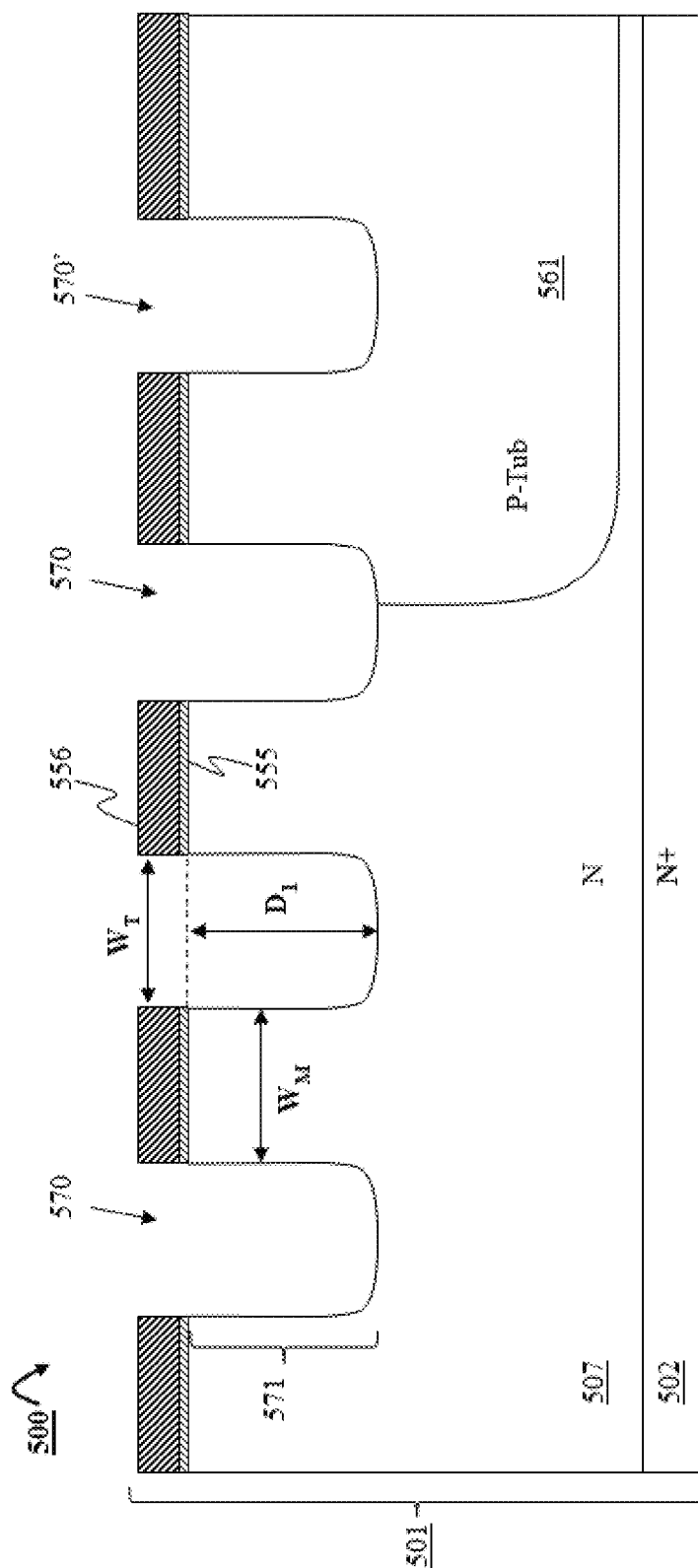
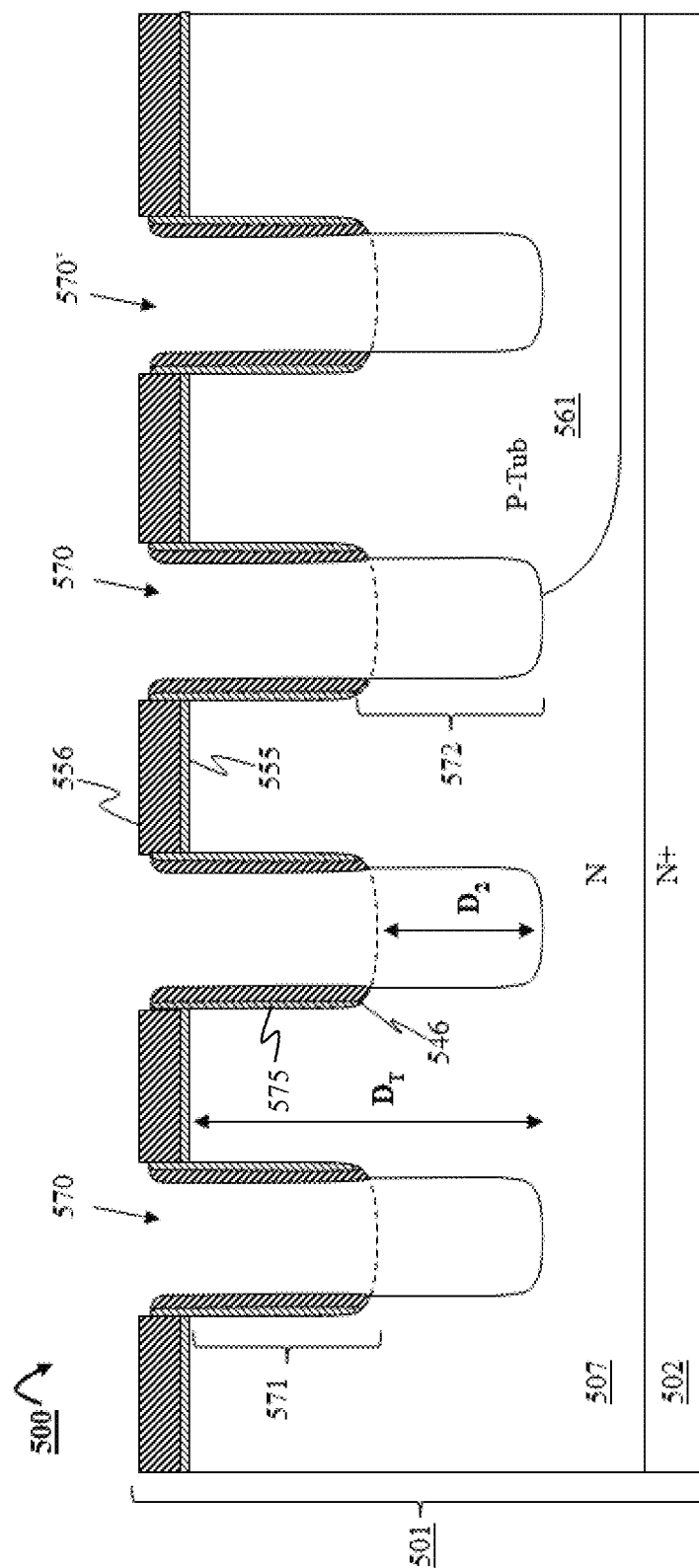


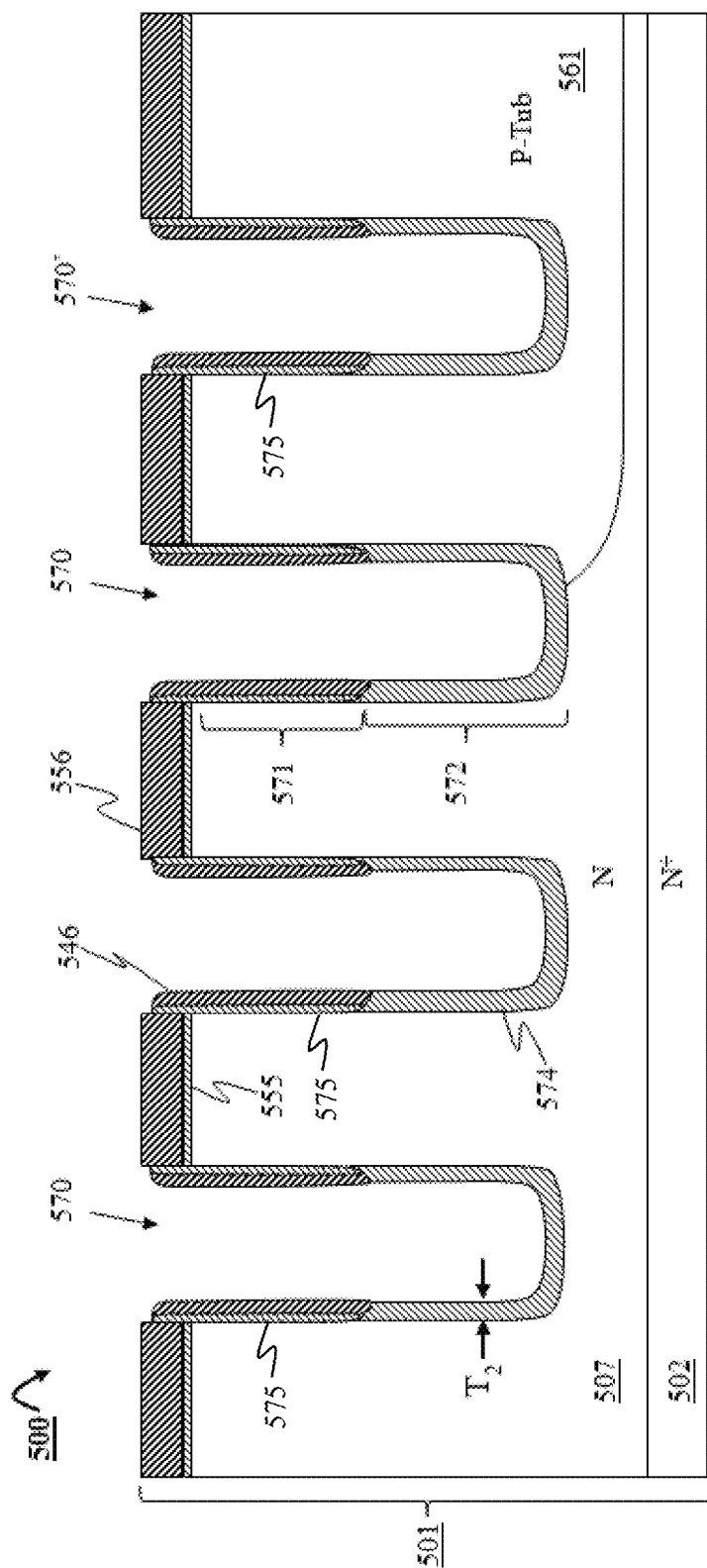
FIG. 5B



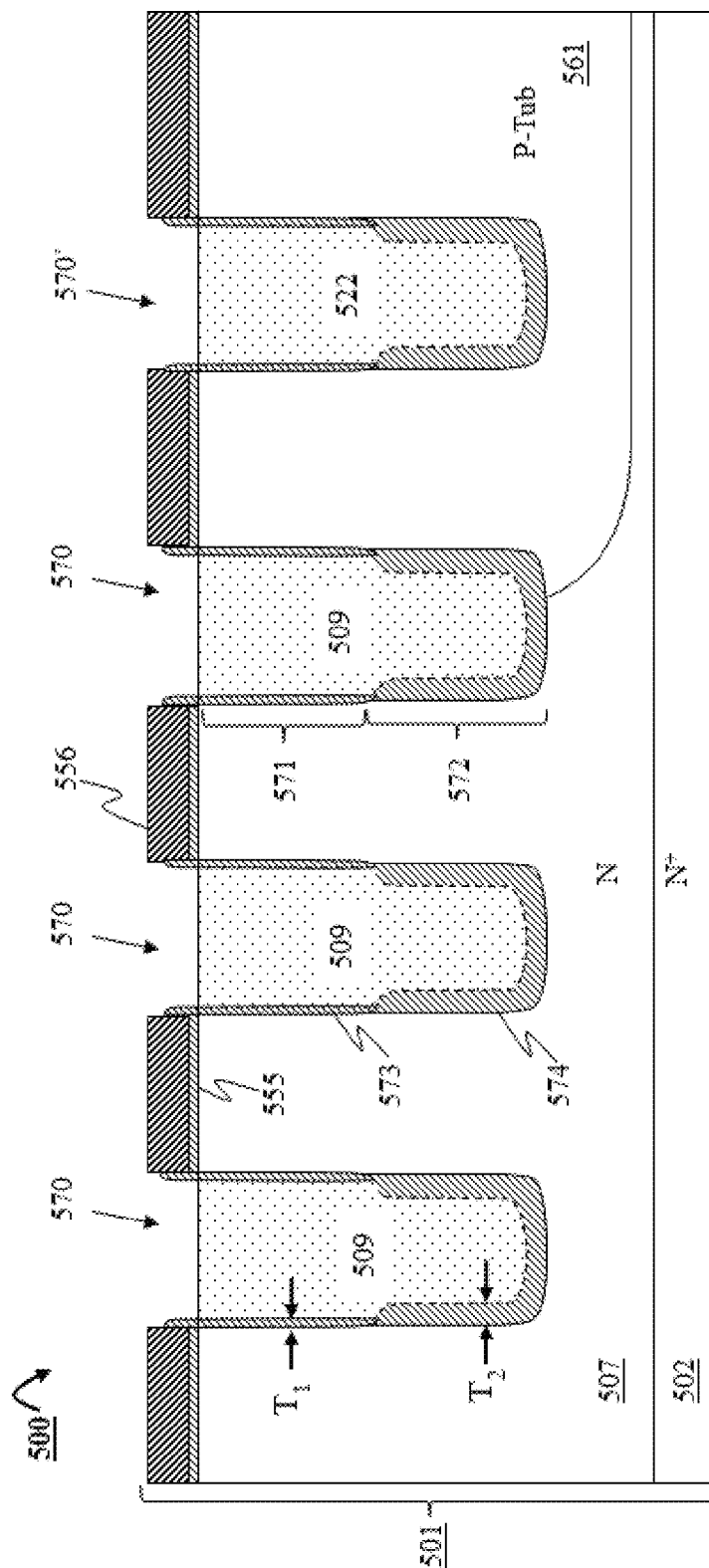
**FIG. 50**



**FIG. 5D**

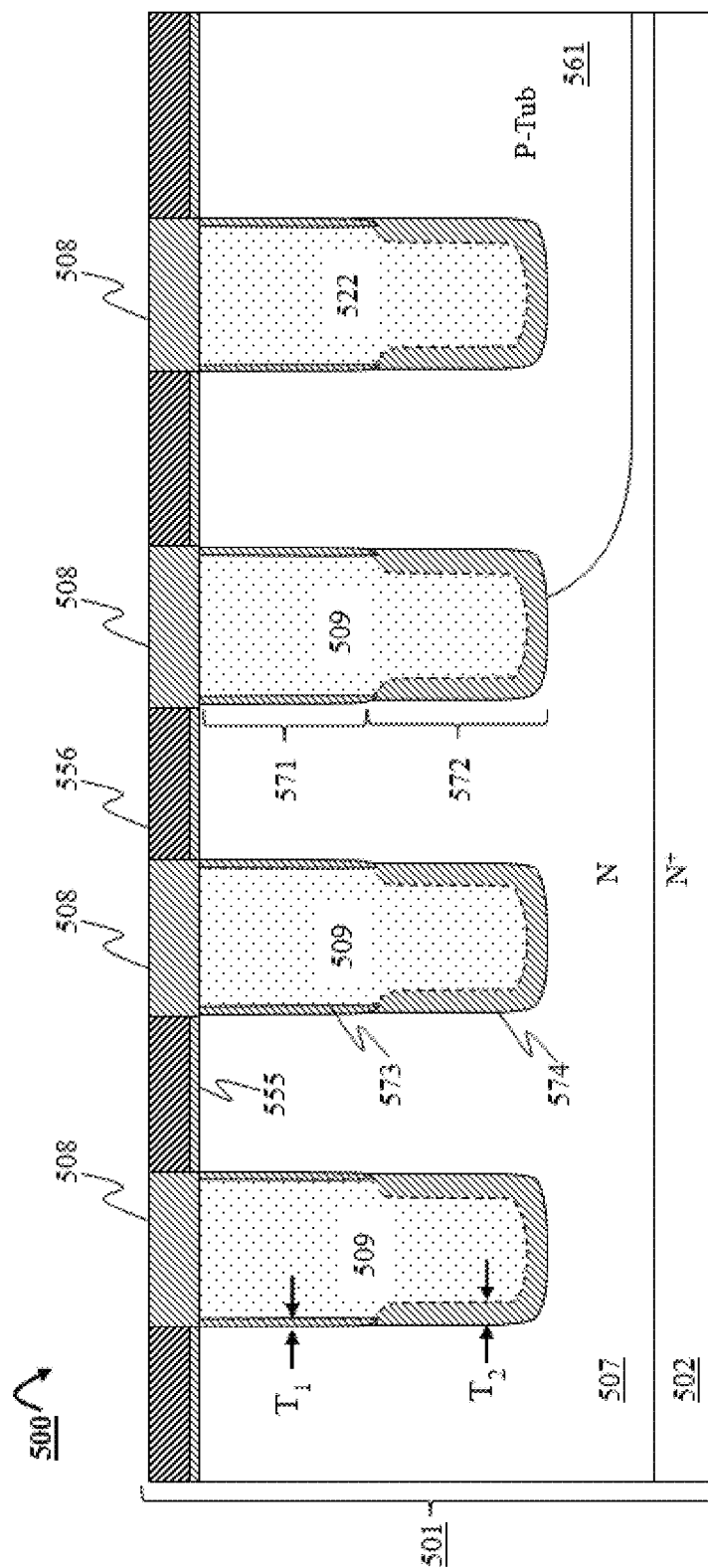


**FIG. 5E**



**FIG. 5F**





**FIG. 5G**

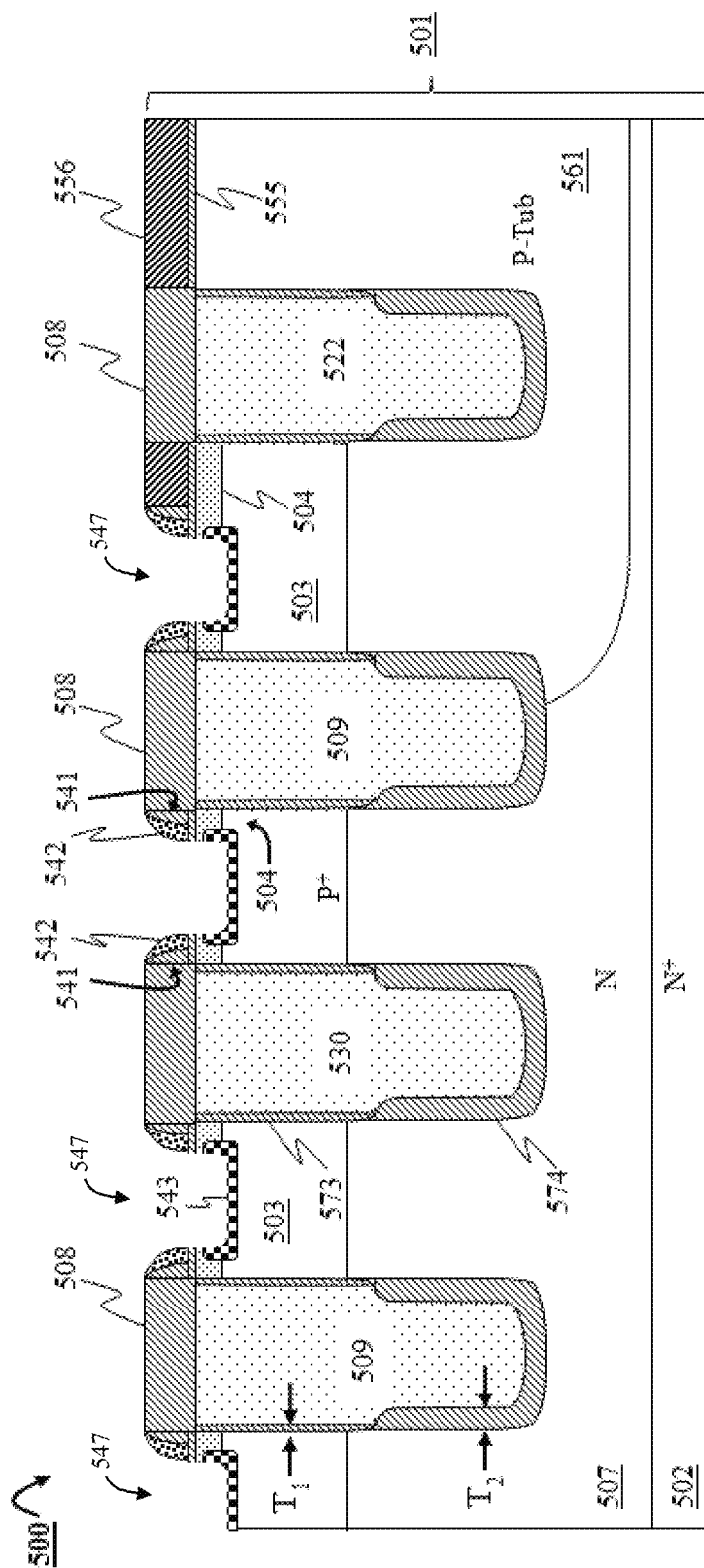
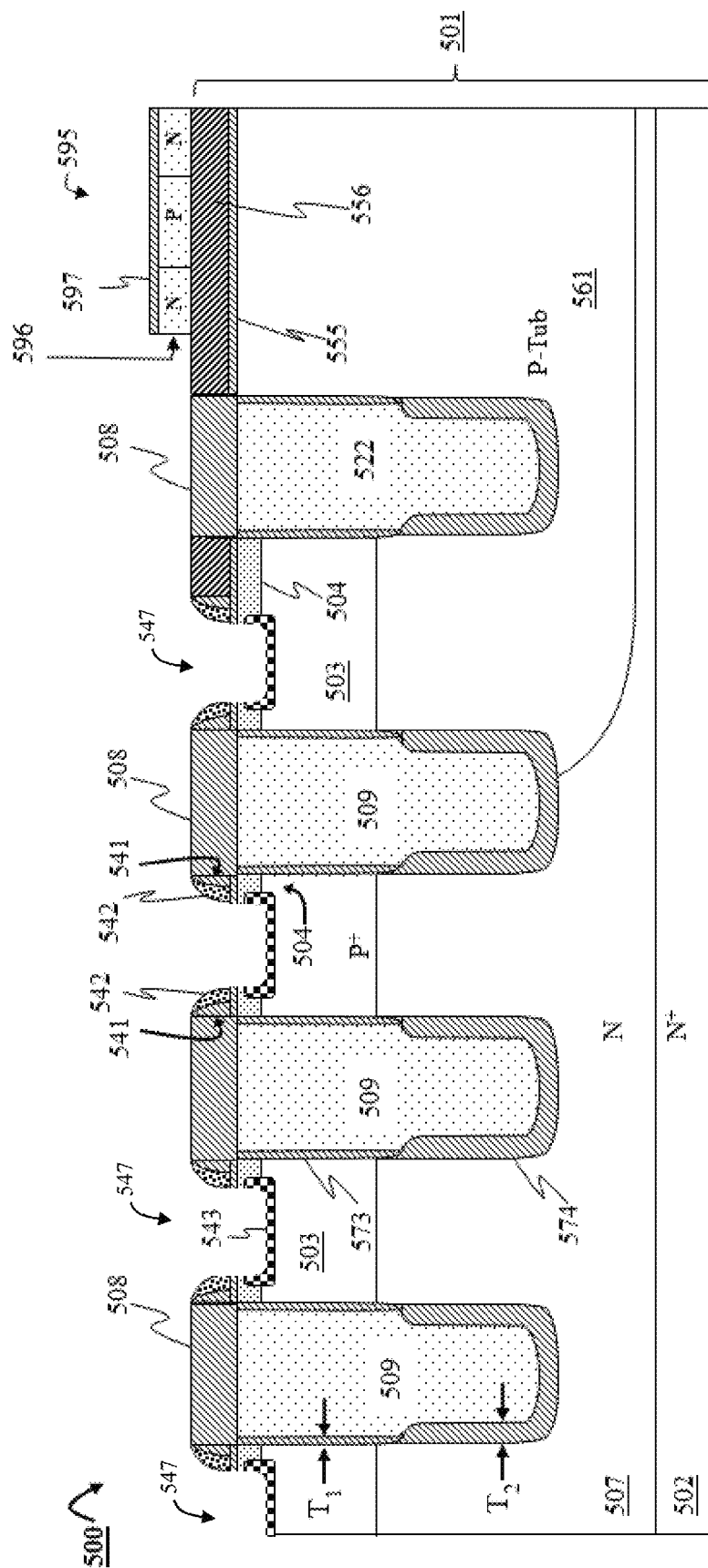
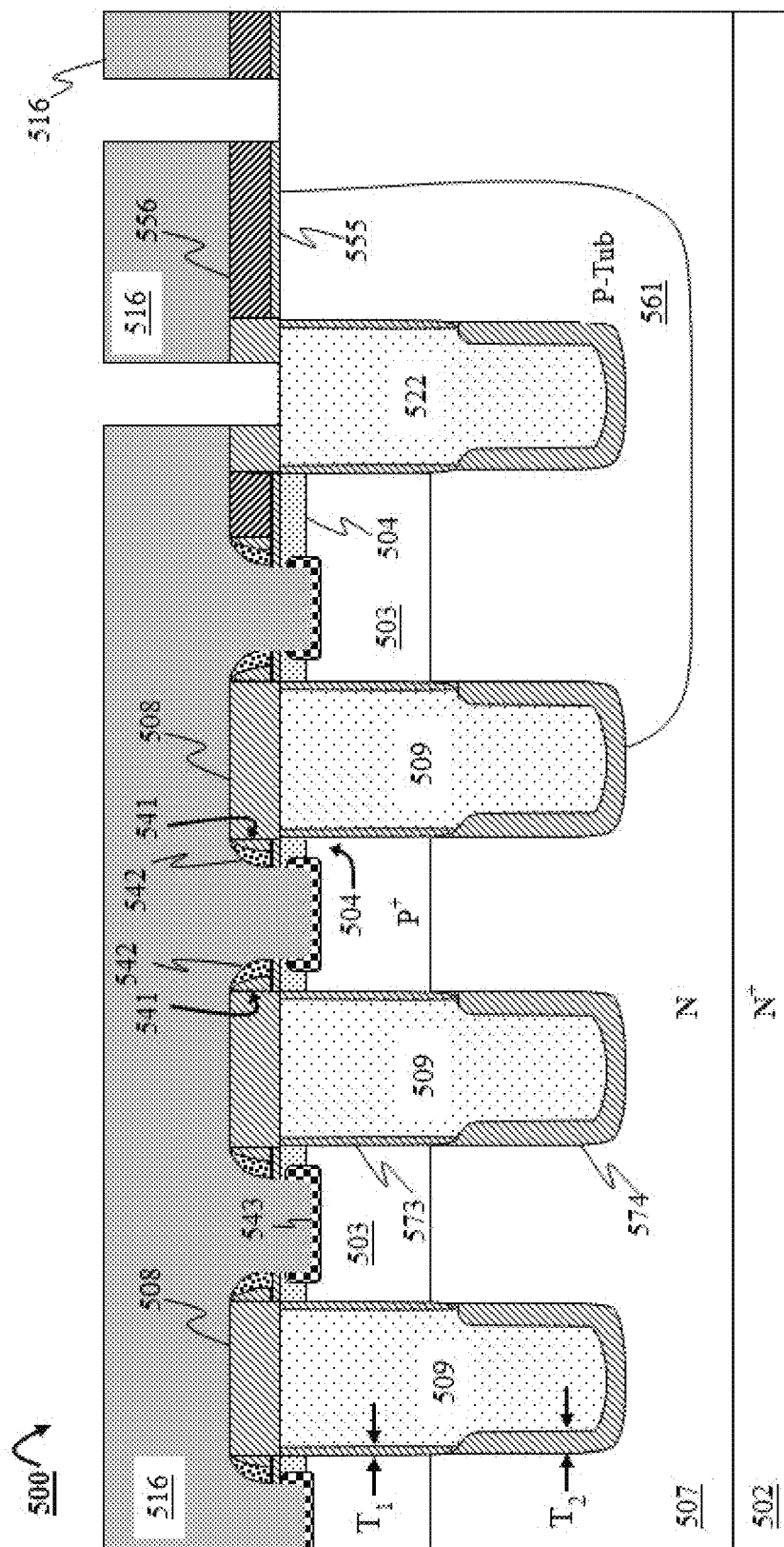


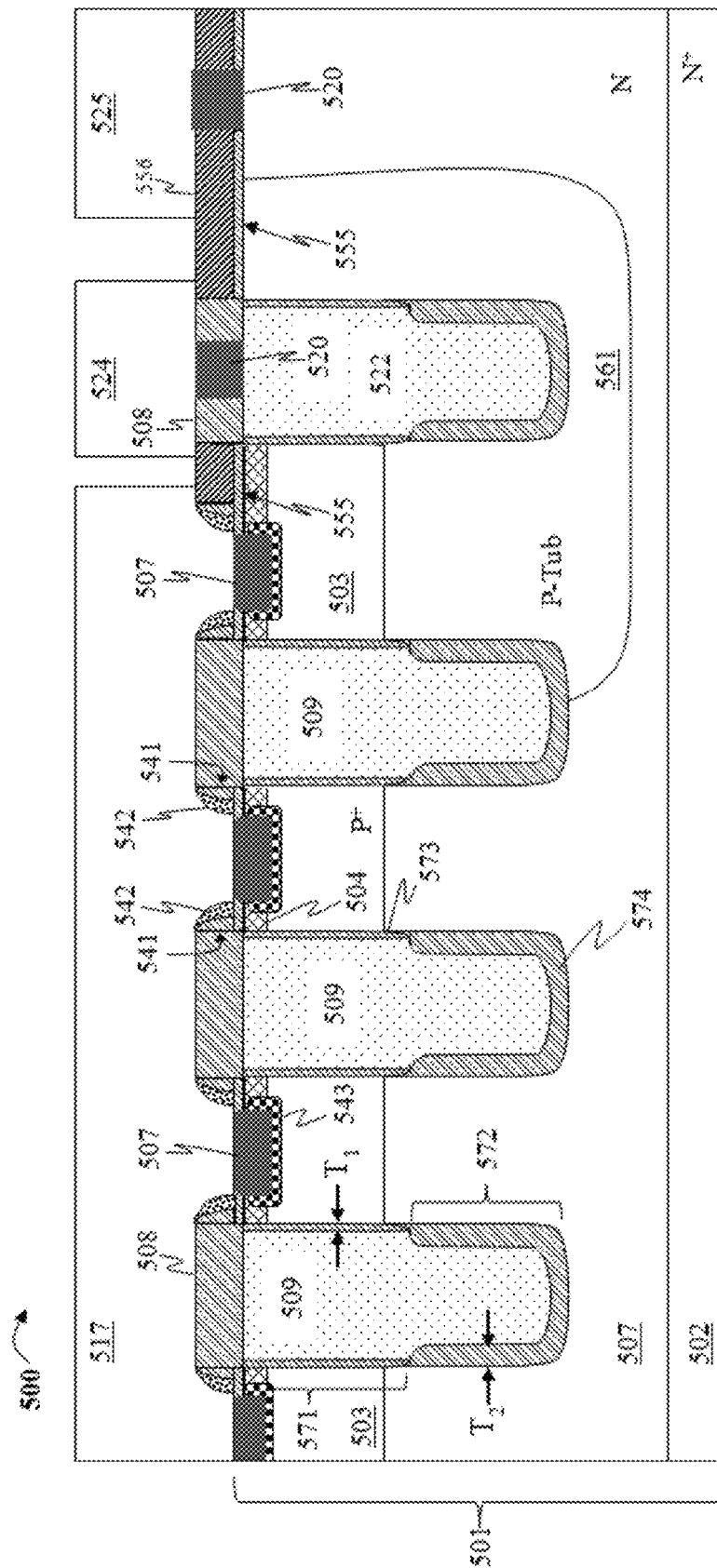
FIG. 5H



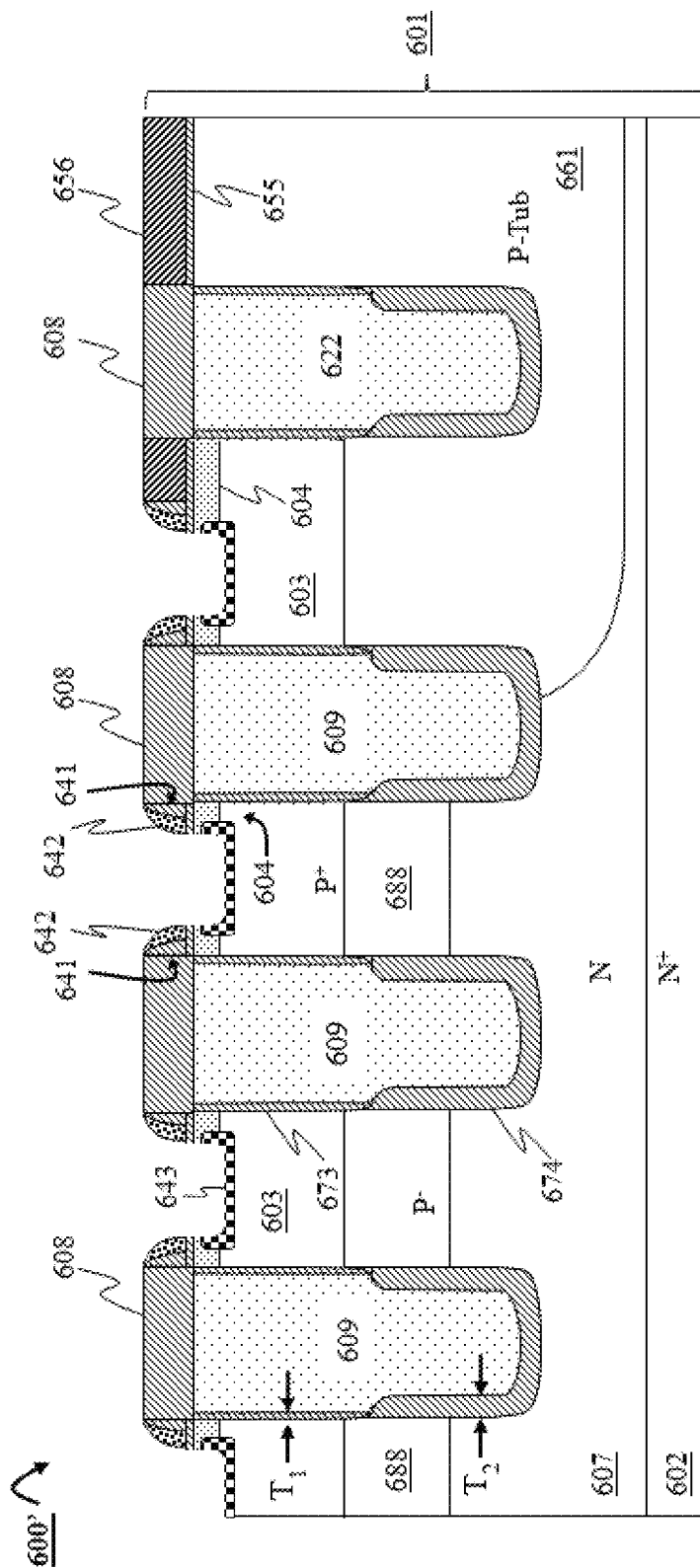
**FIG. 5H**



**FIG. 51**



**361**



**FIG. 6A**

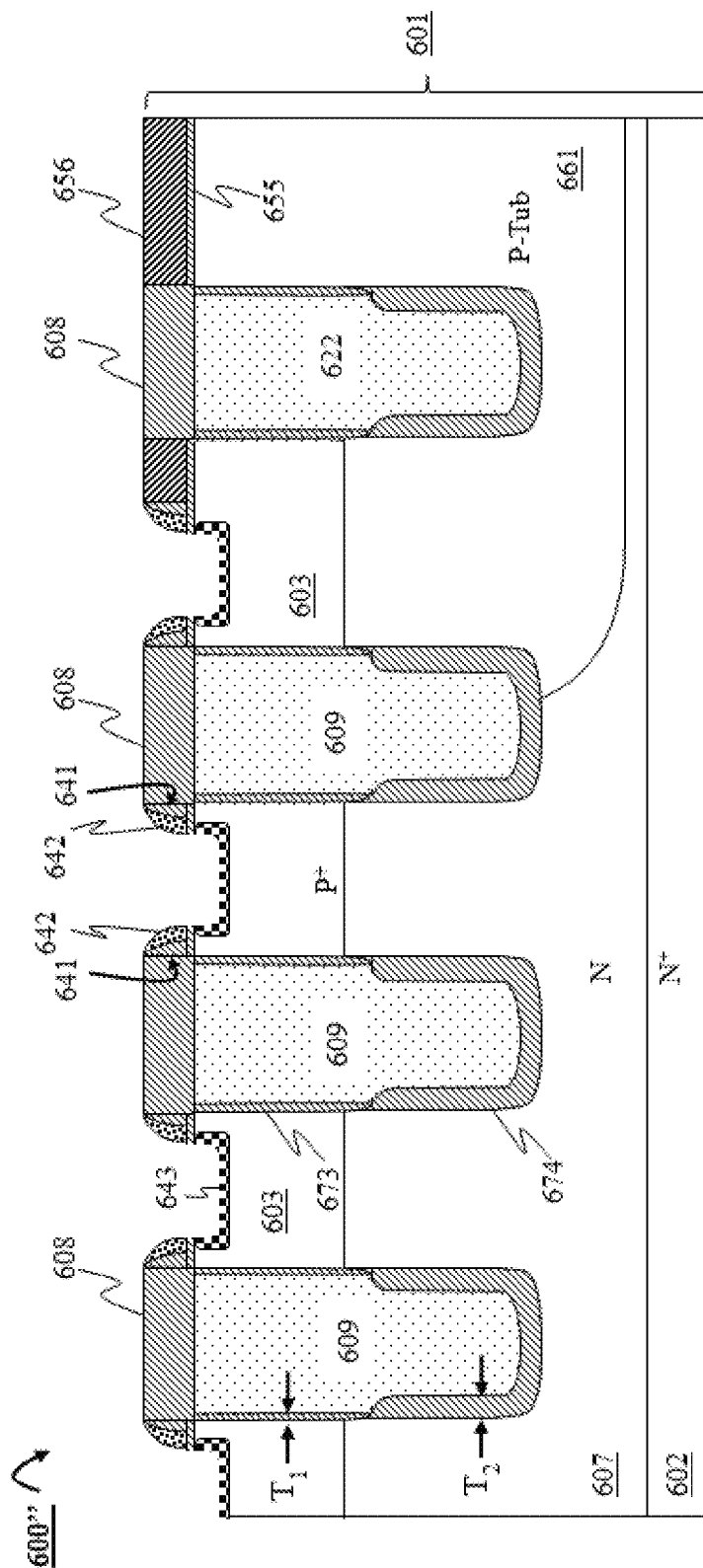


FIG. 6B

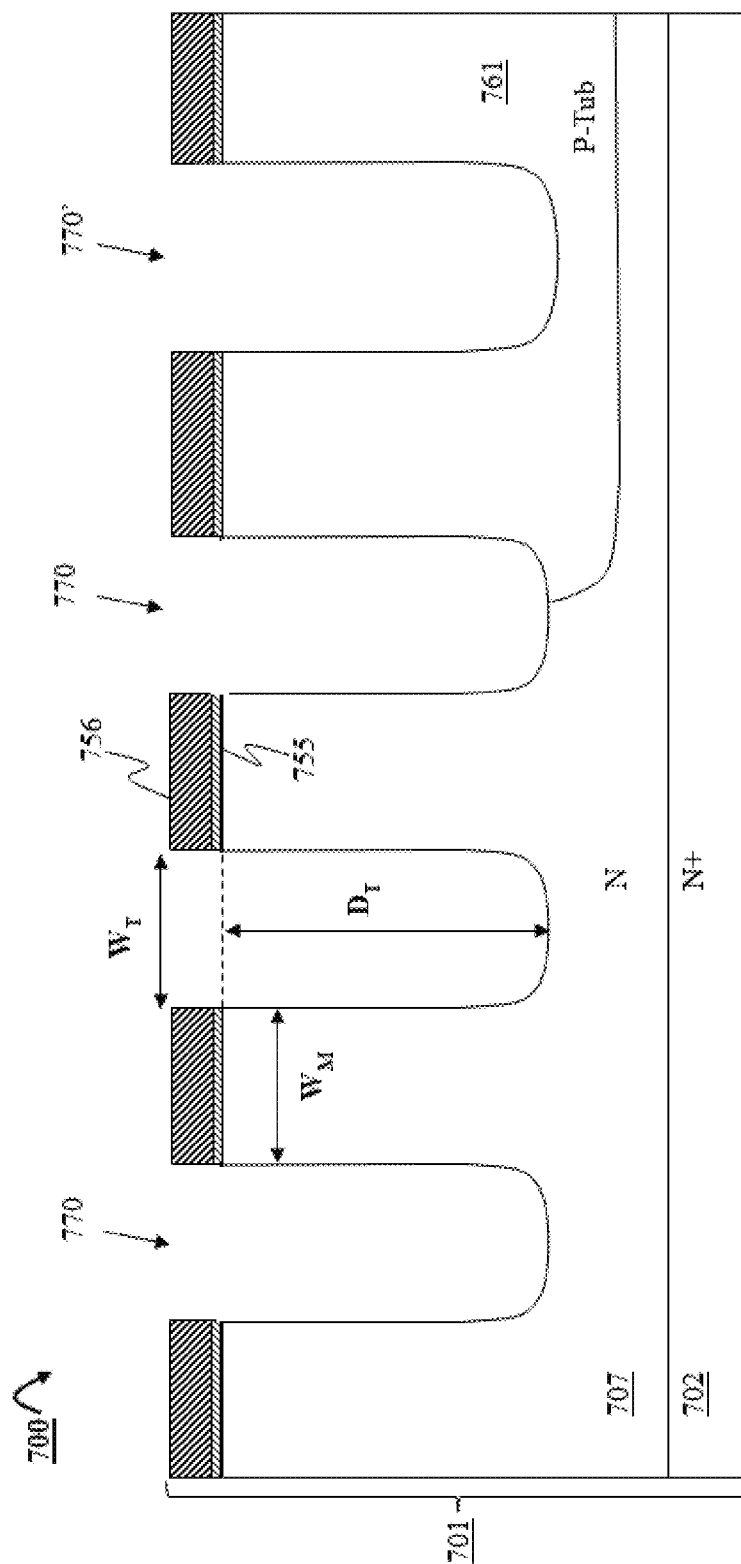


FIG. 7A



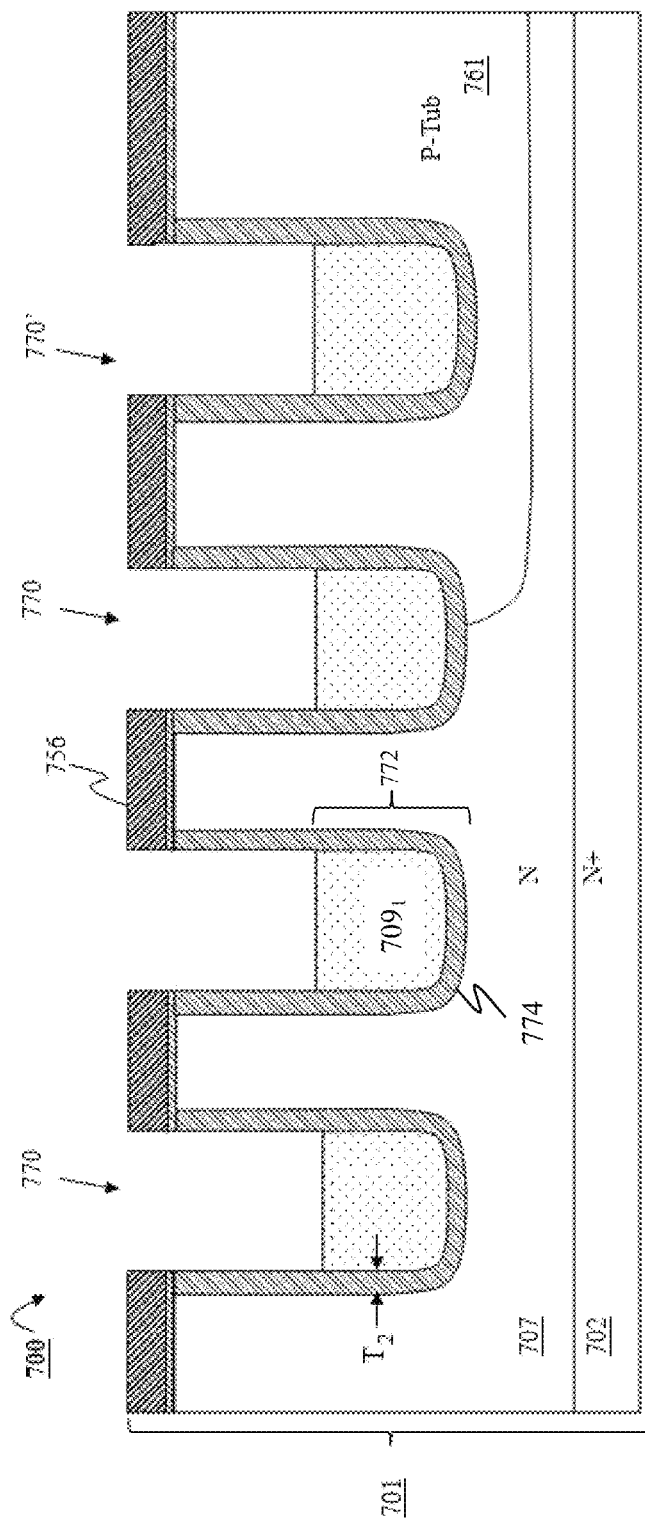
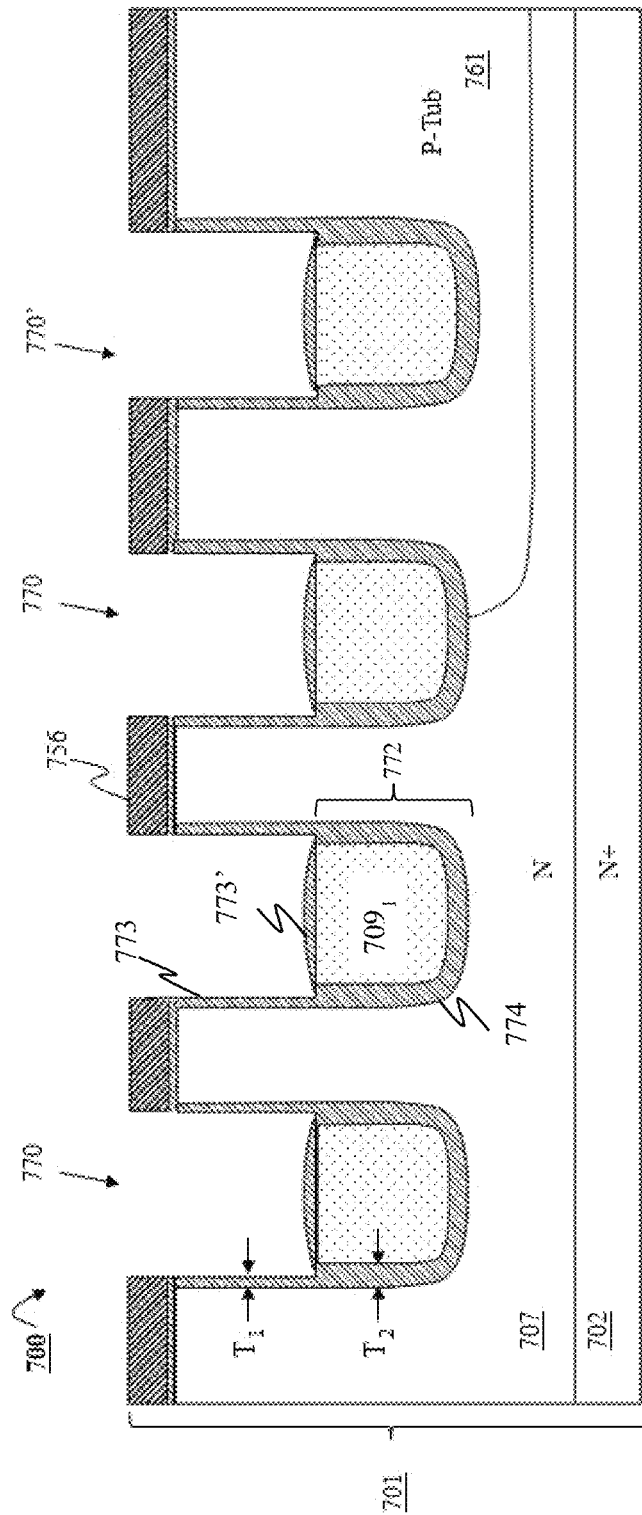
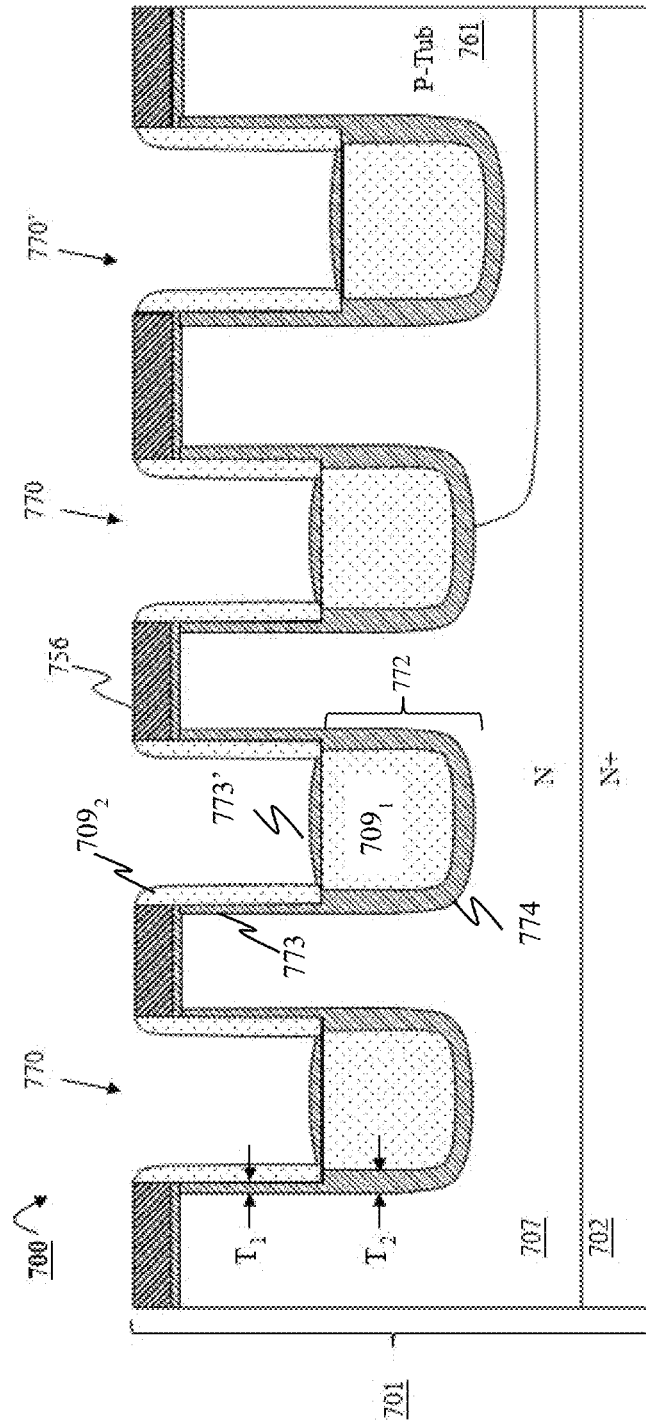


FIG. 7B



**FIG. 7C**



**FIG. 7D**

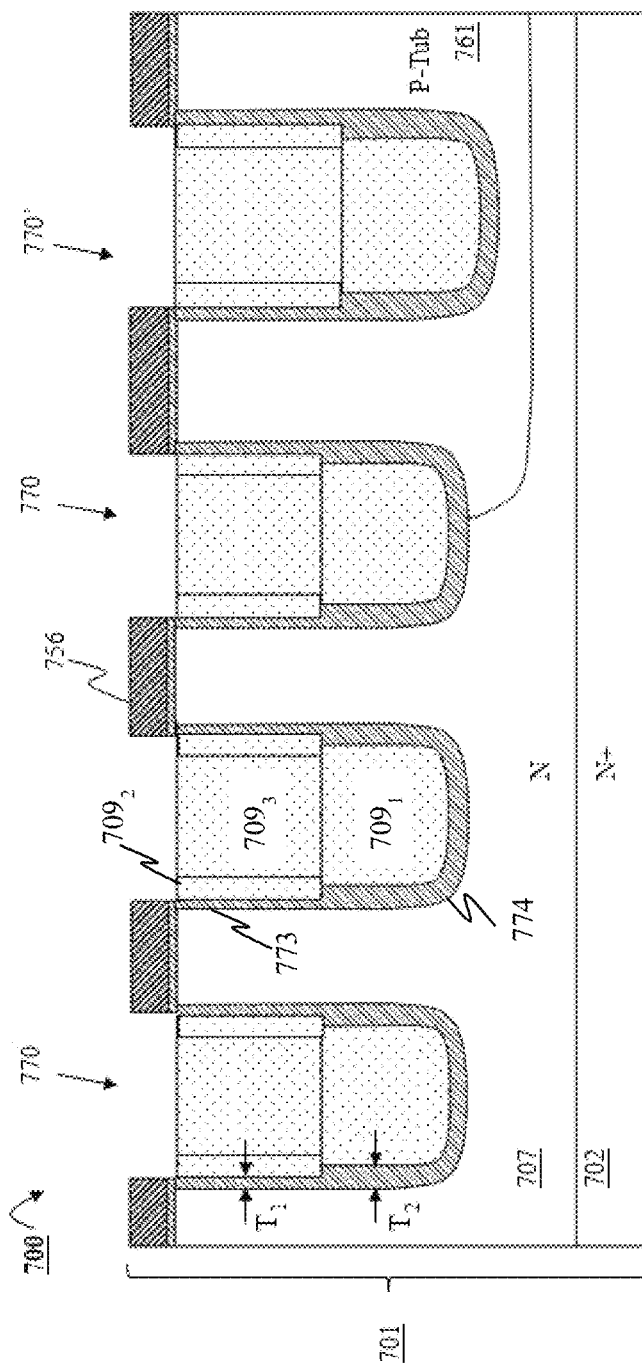


FIG. 7E

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# DEVICE STRUCTURE AND METHODS OF MAKING HIGH DENSITY MOSFETS FOR LOAD SWITCH AND DC-DC APPLICATIONS

## CLAIM OF PRIORITY

This application is a continuation of commonly-assigned, co-pending U.S. patent application Ser. No. 14/329,806, filed Jul. 11, 2014, the entire disclosures of which are incorporated herein by reference. U.S. patent application Ser. No. 14/329,806 is a divisional of commonly-assigned, co-pending U.S. patent application Ser. No. 13/724,180 (now U.S. Pat. No. 8,809,948), filed Dec. 21, 2012, the entire disclosures of which are incorporated herein by reference.

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to commonly-assigned, co-pending application Ser. No. 13/724,228, now U.S. Pat. No. 8,946,816, filed Dec. 21, 2012 and entitled "HIGH DENSITY TRENCH-BASED POWER MOSFETS WITH SELF-ALIGNED ACTIVE CONTACTS AND METHOD OF MAKING SUCH DEVICES" to Lee, Chang, Kim, Lui, Yilmaz, Bobde, Calafut, and Chen, the entire disclosures of which are incorporated herein by reference.

This application is related to commonly-assigned, co-pending application Ser. No. 13/724,093, now U.S. Pat. No. 8,753,935, filed Dec. 21, 2012 and entitled "HIGH FREQUENCY SWITCHING MOSFETS WITH A LOW OUTPUT CAPACITANCE USING A DEPLETABLE P-SHIELD" to Bobde, Yilmaz, Lui, and Ng, the entire disclosures of which are incorporated herein by reference.

## FIELD OF THE INVENTION

This invention generally relates to metal oxide silicon field effect transistors (MOSFETs) and more particularly to high density trench based power MOSFETs.

## BACKGROUND OF THE INVENTION

Low voltage power MOSFETs are often used in load switching applications. In load switching applications it is desirable to reduce the on-resistance ( $R_{ds}$ ) of the device. Specifically, the  $R_{dsA}$  of the device needs to be minimized, where  $R_{dsA}$  is the on-resistance of the device multiplied by the active area of the device. Additionally, low voltage power MOSFETs are commonly used in high frequency DC-DC applications. In such applications it is often desirable to maximize the device's switching speed. Three of the most important parameters for optimizing the switching speed are: 1)  $R_{ds} \times Q_g$ ; 2)  $R_{ds} \times Q_{OSS}$ ; and 3) the ratio of  $Q_{gd}/Q_{gs}$ . First, the product of the  $R_{ds}$  and the gate charge ( $Q_g$ ) is a measure of the device conduction and switching losses together.  $Q_g$  is the sum of the gate to drain charge ( $Q_{gd}$ ) and the gate to source charge ( $Q_{gs}$ ). In the second parameter,  $Q_{OSS}$  is a measure of the capacitances that need to be charged and discharged whenever the device is switched on or off. Finally, minimizing the ratio of  $Q_{gd}/Q_{gs}$  reduces the possibility of the device turning on due to a large  $dV/dt$  when the device is being switched off.

Trench based MOSFETs, as shown in FIG. 1A, were designed in part in order to reduce  $R_{dsA}$  of the device. The design of trench based MOSFETs allowed for the removal of the JFET structure that was present in planar MOSFETs. By

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eliminating the JFET, the cell pitch could be reduced. However, the basic trench based MOSFET does not have any charge balancing in the drift regions, and therefore causes an increase in the  $R_{dsA}$ . Also, the relatively thin gate oxide generates a high electric field under the trench, which leads to a lower breakdown voltage. Low doping concentrations are needed in the drift region in order to support the voltage, and this increases the  $R_{dsA}$  for structures with thinner gate oxides. Further, as cell pitch continues to decrease, the trench based MOSFET may become a less desirable choice because of the difficulty in reducing the thickness of the gate oxide further.

Previous attempts have been made to solve these problems through various designs. A first example is a shielded gate MOSFET as shown in FIG. 1B and described in U.S. Pat. No. 5,998,833 to Baliga. The use of a trench-based shield electrode connected to source potential instead of a larger gate electrode reduces the gate-to-drain capacitance ( $C_{gd}$ ) of the MOSFET and improves switching speed by reducing the amount of gate charging and discharging needed during high frequency operation. However, the MOSFET device described by Baliga exhibits a high output capacitance because the source potential is capacitively coupled to the drain via the shield electrode. Also, in order to sustain the blocking voltage a thick oxide is required. Finally, complex processing is required in order to produce two electrically separated polysilicon electrodes within the same trench. The complexity of the fabrication is further accentuated when the pitch of the device is scaled downwards to the deep sub-micron level.

Finally, the MOSFET design shown in FIG. 1C and described in U.S. Pat. No. 4,941,026 to Temple, has certain characteristics that may be utilized to optimize the switching characteristics of a device. The device in Temple utilizes a two-step gate oxide with a thin layer of oxide near the top of the gate and a thicker layer of oxide in the bottom portion of the gate in order to create a device that has a low channel resistance and a low drift resistance. The thin upper portion of the gate oxide provides good coupling between the gate and body region which generates a strong inversion and low on-resistance in a channel next to the thin upper portion. The thicker gate oxide on the bottom creates a charge balancing effect and allows for the drift region to have an increased doping concentration. A higher doping concentration in the drift region decreases its resistance.

However, the device shown in FIG. 1C is not easily downwards scalable because it is highly susceptible to body contact misalignment errors. For example, if the pitch of the devices was scaled to the deep sub-micron level e.g., 0.5-0.6  $\mu\text{m}$ , then the contact mask misalignment, relative to the gate, may greatly alter the characteristics of the device. In order to provide a good ohmic contact to the body region, an ohmic contact that is highly doped with dopants of the same conductivity type as the body region may be implanted after the contact mask has been used. If the contact mask is aligned too close to the gate, namely not landing exactly at the center of the silicon mesa, then highly doped implants used to generate an ohmic contact with the body may end up in the channel. If the highly doped ohmic region is in the channel, then the threshold voltage and the on-resistance of the device will be impacted. Also, if the contact mask is aligned too far away from the gate, then the turn on of the bipolar junction transistor (BJT) becomes an issue. Since the contact is further from the trench, the length of the body region is increased and therefore so is its resistance. As the resistance of the body region increases, it increases the voltage drop across the body region. The larger voltage drop

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across the body region will make it easier for the parasitic BJT to turn on and ruin the device.

Therefore, in order to fabricate deep sub-micron devices that are optimized for use as load switches and high frequency DC-DC applications there is a need for a device and method capable of self-aligning the contacts to the gate in order to prevent the aforementioned side effects.

It is within this context that embodiments of the present invention arise.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-1C are prior art MOSFET devices.

FIGS. 2A-2C are diagrams and a graph that explain the electrical characteristics of the MOSFET devices according to aspects of the present disclosure.

FIGS. 3A-3E are cross-sectional diagrams of several MOSFET devices according to aspects of the present disclosure.

FIG. 4 is an overhead layout pattern of a MOSFET device according to aspects of the present disclosure.

FIGS. 5A-5J are cross-sectional diagrams that describe a method for fabricating a MOSFET device according to aspects of the present disclosure.

FIGS. 6A-6B are cross-sectional diagrams that describe alternate methods for fabricating a MOSFET device according to aspects of the present disclosure.

FIGS. 7A-7E are cross-sectional diagrams that describe an alternative method for forming the two step gate oxide of the MOSFET device according to aspects of the present disclosure.

#### DESCRIPTION OF THE SPECIFIC EMBODIMENTS

Although the following detailed description contains many specific details for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the exemplary embodiments of the invention described below are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention. In the following discussion, an N-type device is described for purposes of illustration. P-type devices may be fabricated using a similar process but with opposite conductivity types.

Aspects of the present disclosure describe a high density trench-based power MOSFET with self-aligned source and body contacts. The source/body contacts may be self-aligned with conductive or semiconductor (e.g., doped polysilicon) spacers. The spacers may be formed along the sidewall of the gate caps. Additionally, the active devices may have a two-step gate oxide, wherein a lower portion of the gate oxide has a thickness  $T_2$  that is larger than the thickness  $T_1$  of an upper portion of the gate oxide. The two-step gate oxide combined with the self-aligned source/body contacts allow for a highly scalable device that is capable of being produced with an active device pitch in the deep sub-micron level, e.g., 0.5-0.6 microns.

Additional aspects of the present disclosure describe a similar device that does not have a source region formed in the silicon epi part of the device. According to this aspect of the present disclosure, the semiconductor spacers, e.g., N<sup>+</sup>-doped polysilicon spacers, may also serve as the source region, and therefore the addition of a source region within the substrate may be omitted. Additional aspects of the present disclosure describe a similar device where the source

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region formed in the silicon epi part of the device is formed by diffusing dopants from the doped polysilicon spacers into the silicon epi part of the device.

Additional aspects of the present disclosure describe a high density trench-based power MOSFET with self-aligned source contacts that is adapted for high switching speeds. In addition to the self-aligned source contacts and two-step gate oxide, the fast switching MOSFET further comprises a lightly doped P-region below the body region. The lightly doped P-region reduces the coupling between the gate and the drain of the device.

The two step gate oxide allows for a significant portion of the voltage to be supported by a lower portion of the gate oxide 374. This reduces the amount of voltage that the epitaxial layer 307 must support. FIG. 2A is a cross sectional view of an active device that displays the strength of the electric field, where darker shading indicates a higher electric field strength. As shown by the heavy shading along the bottom portion of the trench, the lower portion of the gate oxide 374 supports a large portion of the electric field. FIG. 2B is a graph depicting voltage that has been blocked by device 300 versus the depth into the substrate. Device 300 begins blocking voltage at a depth of approximately 0.5 microns. This depth is consistent with the depth at which the lower portion of the gate oxide 374 with a thickness  $T_2$  begins. Near the bottom of the trench and the oxide 374 (about 1.0 microns) the device has blocked a total of approximately 18 volts. This greatly reduces the voltage blocking burden of the epitaxial layer 307. Therefore, the doping concentration of epitaxial drift layer 307 may be increased in order to reduce the  $R_{dsA}$  of device. The increase in the doping concentration of the epitaxial layer 307 along with lower channel resistance due to smaller cell pitch allows for an approximately 90% or more decrease in the  $R_{dsA}$  when compared to the prior art trench based MOSFET designed to support the same voltage described in FIG. 1A, or an approximately 37% or more decrease in the  $R_{dsA}$  when compared to the prior art split gate MOSFET designed to support the same voltage described in FIG. 1B.

The  $R_{dsA}$  of the device is further decreased because of the location of the accumulation region 391. As shown in FIG. 2C, when the gate is turned on a narrow accumulation region 391 is formed in the upper portion of the epitaxial layer 307 adjacent to the trench sidewall. By way of example, the accumulation region 391 may be approximately 300-400 Å wide. This concentration of charge carriers along the accumulation region reduces the resistance over the upper portion of the epitaxial layer 307. Further, since the accumulation region 391 is thin, reducing the cell pitch does not affect the resistance as long as the pitch is greater than the width of the accumulation region 391. This feature is not present in a split gate MOSFET device of the type described above with respect to FIG. 1B. In that type of device, the lower portion of the trench is kept at the source potential, which prevents an accumulation region 391 from forming along a narrow path proximate to the sidewall. Therefore, it is not practical to shrink the pitch of the split gate MOSFET to the deep sub-micron level.

FIG. 3A is a cross sectional view of a device structure 300 according to aspects of the present disclosure. The device structure 300 may be built on a semiconductor substrate 301. The substrate 301 may be suitably doped to be an N-type or a P-type substrate. As used herein, the substrate 301 will be described as an N-type substrate. The semiconductor substrate 301 may comprise a heavily doped N<sup>+</sup> drain region 302 and an epitaxial layer 307. By way of example, the drain region 302 may have a doping concentration of approxi-

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mately  $10^{19} \text{ cm}^{-3}$  or greater. The epitaxial layer 307 may be grown above the drain region 302 and may be lightly doped with N-type dopants. By way of example, the epitaxial layer 107 may have a doping concentration that is approximately between  $10^{15} \text{ cm}^{-3}$  and  $10^{17} \text{ cm}^{-3}$ . A suitably doped P-body layer 303 may be formed in a top portion of the epitaxial layer 307. An N<sup>+</sup>-doped source region 304 may be formed in a top portion of the body layer 303.

According to aspects of the present disclosure, the active area of the device structure 300 may comprise a plurality of trench based power MOSFETs. The trench based power MOSFETs are formed by creating a trench 370 that extends through the P-body region 303 and into the epitaxial layer 307. Each trench may have an upper portion 371 and a lower portion 372. The upper portion of the trench 371 may be lined with an upper insulative layer 373 that has a thickness  $T_1$ , and the lower portion of the trench 372 may be lined with a lower insulative layer 374 that has a thickness  $T_2$ . According to aspects of the present disclosure, it is desirable that the thickness  $T_1$  be smaller than the thickness  $T_2$ . By way of example, the upper and lower insulative layers may be an oxide. The remainder of the trench may be filled with a suitable material to form a gate electrode 309. By way of example, the gate electrode 309 may be formed with polysilicon. Though not shown in FIG. 3A, gate electrodes 309 are connected to a gate pad and are maintained at a gate potential. Each gate electrodes 309 is electrically isolated from a source material 317 by an insulative gate cap 308 which is disposed above the trench. An insulative layer 355 may also be formed above the source region 304. The possibility of short circuiting the gate electrode 309 to the source material 317 may be reduced by forming an insulative spacer 341 along the vertical edges of the gate caps 308. By way of example, the insulative spacer 341 may be an oxide.

The source regions 304 are electrically connected to the source material 317 through self-aligned contact openings 389 in the substrate that extend through the insulating layer 355 and the source region 304. The openings 389 are self-aligned by the N<sup>+</sup>-doped polysilicon spacers 342 formed along the exposed sidewall of the insulative spacers 341. These spacers function as a mask layer for an etching process used to form the contact openings 389. The N<sup>+</sup>-doped polysilicon spacers 342 reduce the contact resistance by increasing the area of contact to the source and allow for the formation of an ohmic contact. By way of example and not by way of limitation, the electrical connections may be made with conductive plugs 357. By way of example and not by way of limitation, the conductive plugs 357 may be made from a conductive material such as tungsten. An ohmic contact between the conductive plugs 357 and the P-body layer 303 may be improved by the addition of an ohmic contact region 343. The ohmic contact region 343 is a highly doped P-region that is formed on the exposed surface of the self-aligned contact openings 389. By way of example, the ohmic contact region 343 may be formed by implanting P-type dopants such as boron with a doping concentration of approximately  $1 \times 10^{19} \text{ cm}^{-3}$ .

The self-aligned contact openings 389 may be formed sufficiently close to each other such that the active devices in the MOSFET device have a pitch P of less than 1.0 microns. More specifically, aspects of the present disclosure allow for the devices to have a pitch P of less than 0.6 microns. This pitch is made possible in because the self-alignment of the contact openings 389 eliminates alignment errors even when the devices are scaled to have a pitch below 1.0 micron. This ensures that threshold voltage of the

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device is maintained, because the dopants from the ohmic contact region 343 remain outside of the channel. Additionally, the self-alignment of the contact openings 389 allows for precise control of the parasitic BJT turn on because the distance between the trench sidewall and the conductive plug will be substantially constant across the device. Consistent spacing makes the resistance of the body region and the voltage drop across the body region substantially constant across the device as well. Therefore, there will be little variation in the conditions that will cause the parasitic BJT to turn on for each active device.

According to another additional aspect of the present disclosure, a device structure 300' may also be configured for fast switching applications such as DC-DC applications. FIG. 3B depicts a structure 300' that is substantially similar to device 300 in FIG. 3A, but with the addition of a sub-body layer 388. The sub-body layer 388 is a lightly doped P-layer formed below the P-body layer 303 and electrically connected to the source metal. The dopant concentration of the sub-body layer 388 should be low enough to allow for an inversion channel to be formed proximate to the lower insulative layer 374. The doping range for the lightly doped sub-body layer 388 may be from about  $1 \times 10^{14} \text{ cm}^{-3}$  to about  $1 \times 10^{16} \text{ cm}^{-3}$ . Adding the sub-body layer 388 to device 300' reduces the coupling between the gate electrode and the drain electrode, and therefore provides significant decreases in the values of  $Q_g$ ,  $Q_{gd}$ , and  $Q_{oss}$ . Further the  $R_{ds-on}$  of the device is only slightly increased. As described above these variables are included in the key figures of merit for determining the switching speed of a device. By maximizing  $Q_g$ ,  $Q_{gd}$ , and  $Q_{oss}$  with only a slight increase in  $R_{ds-on}$ , the switching speed of device 300' may be greatly improved. The sub-body layer 388 may extend to a depth below the top portion of the trench 371. As the depth of the sub-body layer 388 increases the improvements in the switching speed increase as well. However, the increase in depth also increases the  $R_{ds-on}$ .

FIG. 3C depicts a device 300'' according to an additional aspect of the present disclosure that omits the source region 304 from the top portion of the semiconductor substrate 301. Other than the removal of source region 304, device 300'' is substantially similar to that of device 300 described in FIG. 3A. The source region 304 may be omitted because the N<sup>+</sup>-doped polysilicon spacer 342 may also serve as the source region due to its high concentration of N-type dopants. The utilization of the N<sup>+</sup>-doped polysilicon spacers 342 as the source region allows for the reduction of a source implantation step during processing, and significantly suppress the parasitic bipolar action.

Device 300 may optionally include an electrostatic discharge (ESD) protection structure 395 as shown in FIG. 3D. The ESD protection structure 395 may be a conductive material 396 formed over a first layer 356 of a two layer hardmask. The conductive material 396 may be selectively doped to include N-type and P-type regions. An insulative layer 397 may be formed over a top surface of the conductive material 396.

Device 300 may also optionally include one or more gate pickup trenches 370' as shown in FIG. 3D. The gate pickup trench 370' is substantially similar to the active device trenches 370. However, instead of an electrically insulated gate electrode 309, the gate pickup electrode 322 is electrically connected to a gate metal 324 with an electrical connection 320 that extends through the gate cap 308. By way of example, and not by way of limitation, the electrical connection 320 may be tungsten. The gate pickup trench may be formed in a deep doped region 361 that is doped with

opposite-type dopants to the substrate **301**. By way of example, and not by way of limitation, if the substrate **301** is N-type, the deep doped region **361** would be doped P-type, in which case it is sometimes referred to as a "P-Tub". Alternatively, if the substrate **301** is P-type, the deep doped region **361** would be doped N-type, in which case it is sometimes referred to as an "N-Tub". FIG. **3E** depicts a device **300** that may also optionally include one or more Schottky contacts configured to terminate the electric field. The Schottky contacts in combination with the P-tub **361** may also function as a body clamp (BCL) configured to prevent the active devices from operating above their breakdown voltages. As shown in FIG. **3E**, a metal contact **321** may electrically connect a Schottky metal **325** to the semiconductor substrate **301**. By way of example, the contact **321** may extend through a hardmask having a first layer **356** and a second layer **355**. By way of example, and not by way of limitation, the first layer may be a nitride layer and the second layer may be an oxide layer. By way of example, and not by way of limitation, the metal contacts **321** may be tungsten. The Schottky metal **325** may be deposited over the metal contacts **321** and the first layer of the hardmask **356** and is isolated from the gate metal **324**. Additionally, the gate pickup metal **324** and the Schottky contact **325** are electrically isolated from each other.

FIG. **4** is a diagram of the layout for a device structure **300**. The layout shows the gate electrodes **309** alternating with source contacts **357** in a device region. The source contacts **357** extend perpendicular to the plane of the drawing to make electrical contact with the source metal **317**. Gate runners **319** electrically connect to the gate electrodes **309** to gate pickups **322**. The gate electrodes, gate runners and gate pickups may be made from the same material, e.g., polysilicon, which may be formed in corresponding trenches in a common step. Gate contacts **320** extend perpendicular to the plane of the drawing to make electrical contact with the gate metal **324** (not shown). The gate metal **324** may be initially formed as part of the same metal layer as the source metal **317**. The gate metal **324** may be electrically isolated from the source metal **317** and/or Schottky metal **325**, e.g., by forming a common metal layer followed by subsequent masking, etching and dielectric fill processes, as are commonly done for this purpose.

The BCL regions may be placed outside the active device region, which can be seen from the locations of Schottky contacts **325** in FIG. **4**. Additionally, ESD structures **395** may be formed outside of the active device region. The ESD structures **395** may be formed over an insulator layer **356**. Although the ESD structures **395** are shown as being formed outside the active region, they may also be located outside the gate pickup area.

Aspects of the present disclosure describe methods for fabricating the devices described in FIG. **3A-3E**. Methods of fabrication are described in conjunction with FIGS. **5A-5J** which depict cross sectional views of a device structure **500** at different stages of fabrication.

FIG. **5A** depicts a semiconductor region **501**. The region **501** may be suitably doped to be an N-type or a P-type substrate. For purposes of illustration, the semiconductor region **501** used herein will be an N-type substrate. The semiconductor region **501** may comprise a heavily doped drain contact **502** with a lightly doped epitaxial region **507** grown above the drain contact region **502**. A heavily doped P-tub **561** may be formed in the epitaxial layer **507**. The P-tub may be formed by ion implantation or any other suitable method. By way of example, and not by way of

limitation, a P-tub mask may be used with a masked implantation of P-type dopants.

A hard mask having a first insulating layer **556** and a second insulating layer **555** may be formed on a top surface of the semiconductor substrate **501**. The second insulating layer **555** may be resistant to a first etching process that etches the first insulating layer **556**, and the first insulating layer **556** may be resistant to a second etching process that etches the second insulating layer **555**. By way of example, and not by way of limitation, the first insulating layer **556** may be a nitride layer and the second insulating layer may be an oxide. By way of example, the first insulating layer **556** may be between 0.2 microns ( $\mu\text{m}$ ) and 0.5  $\mu\text{m}$  thick, and the second insulating layer **555** may be between 50 angstroms ( $\text{\AA}$ ) and 250  $\text{\AA}$  thick.

In FIG. **5B** a trench mask may be utilized to define the locations of the trenches **570** by etching through the first and second insulative layers of the hardmask **556**, **555**. Additionally, the gate pickup trenches **570'** may also be defined in the same processing step. Next, in FIG. **5C** a partial trench etch is utilized to form the upper portion **571** of the trenches **570** and **570'**. The upper portion of the trench **571** may be approximately half of the total depth of the trench **570**. By way of example, and not by way of limitation, the depth of the upper portion of the trench **D<sub>1</sub>** may be approximately 0.5  $\mu\text{m}$  deep. Each trench **570** may be spaced apart from other trenches by a mesa with a width  $W_M$ . By way of example the width  $W_M$  may be between 0.2  $\mu\text{m}$  and 0.5  $\mu\text{m}$ . By way of example, the width of each trench  $W_T$  may be between 0.2  $\mu\text{m}$  and 0.5  $\mu\text{m}$ .

In FIG. **5D** the upper portion of the trenches **571** are lined with a thin pad oxide **575** and an insulative spacer **546**. The pad oxide **575** and the insulative spacer **546** prevent the upper portion of the trench **571** from growing an oxide during the processing of the lower portion of the trench **572**. The insulative spacer **546** also functions as an additional mask layer in order to reduce the width of the lower portion of the trench **572**. By way of example, the insulative spacer **546** may be a nitride. After the insulative spacer **546** has been formed, the lower portion of the trench **572** may be formed by an etching process. By way of example, and not by way of limitation, the depth of the second portion of the trench **D<sub>2</sub>** may be an additional 0.5  $\mu\text{m}$ , resulting in a total depth **D<sub>T</sub>** of the trenches **570**, **570'** being approximately 1.0  $\mu\text{m}$ .

Next, in FIG. **5E** a lower insulative layer **574** may be formed. By way of example, but not by way of limitation, the lower insulative layer **574** may be an oxide grown through thermal oxidation. Typically, the thickness  $T_2$  may range from 400  $\text{\AA}$ -1500  $\text{\AA}$ . In FIG. **5F** the pad oxide **575** and the insulative spacers **546** are removed first. Then, the upper insulative layer **573**, which is a gate oxide, may be grown. The thickness  $T_1$  may range from 50  $\text{\AA}$ -500  $\text{\AA}$ . While the ranges for the thicknesses for  $T_1$  and  $T_2$  slightly overlap, it is desirable for the thickness  $T_2$  of the lower insulative portion **574** to be larger than the thickness  $T_1$  of the upper insulative layer **573**. After the upper insulative layer **573** is grown, the trenches **570** and **570'** may be filled with a conductive material in order to form the gate electrode **509** in the active devices and the gate pickup electrode **522** in the gate pickup trench **570'**. In order to minimize the possibility of forming voids within the electrodes **509** and **522** the trenches should have an aspect ratio of width to depth no greater than approximately 1:6. By way of example, and not by way of limitation, the conductive material used to form the electrodes **509** and **522** may be a polysilicon doped with N-type dopants. Once the trenches **570** and **570'** are filled,



the conductive material may be etched down in order to be substantially planar with the top surface of the semiconductor substrate **501**.

In FIG. 5G, the insulative gate caps **508** are formed. The insulative gate caps may be formed with a deposited oxide, such as but not limited, to borophosphosilicate glass (BPSG) or tetraethylorthosilicate (TEOS). After the insulative gate caps **508** have been deposited, they may be planarized with the top surface of the first layer of the hardmask **556**. By way of example, the planarization may be done with chemical mechanical planarization (CMP). By way of example, and not by way of limitation, the thickness of the gate caps **508** may be approximately 300 Å. Gate caps **508** are self-aligned due to the presence of the first and second layers of the hardmask **556** and **555** that were originally etched to form the trench masks. Without the need for an additional mask aligning step, the alignment of the gate caps **508** may be improved. Further, the self-alignment of gate caps **508** provides the foundation for the self-aligning source contacts. Therefore, it is critical that the gate caps **508** be properly aligned.

After the caps **508** have been formed, device **500** may have the first layer of the hardmask **556** removed in the active area with a masking and a first etching process. The first etching process may selectively remove the first layer of the hardmask **556** with little effect on the second layer of the hardmask **555**. By way of example, if the first hardmask layer **556** is a nitride and the second hardmask layer **555** is an oxide, then a hot-phosphoric acid wet dip may preferentially remove the nitride while leaving the oxide. Once the first hardmask layer **556** has been removed, the P-body **503** may be implanted into a top portion of the semiconductor substrate **501**. The N<sup>+</sup>-source region **504** may also be implanted after the first layer of the hardmask **556** has been removed. Next, an insulative spacer **541** may be formed along the sidewalls of the gate caps **508** in order to prevent a short circuit between the gate electrodes **509** and the source metal **517**. The insulative spacers **541** may be formed by depositing an insulation layer on the exposed surfaces of the device and then etching the insulation layer away with an anisotropic etch. The anisotropic etch will leave a portion of the insulative layer along the sidewalls of the gate caps **508** that will function as the insulative spacer **541**. After the oxidation, a polysilicon layer may be disposed along the top surface of the second layer of the hardmask **555**, over the exposed surfaces of the insulative spacer **541**, and over the top surface of the gate caps **508**. The polysilicon layer may be doped with a high concentration of N-type dopants. An anisotropic etch may then be used to remove the polysilicon layer, leaving behind only polysilicon spacers **542** spaced away from the sidewalls of the gate caps **508** by the insulative spacer **541**. By way of example and not by way of limitation, the anisotropic etch process may be a reactive ion etching (RIE). The anisotropic etch process may also etch through the second layer of the hardmask **555**. Additionally, the polysilicon spacers **542** may be used to form the source regions **504** with a diffusion process instead of the implantation step as described above. The source regions **504** may be formed by diffusing N-type dopants from the polysilicon spacer **542** into the top portion of the epitaxial layer **507** below the spacers **542**.

With the top surface of the epitaxial layer **507** exposed, another anisotropic etching process may be used to etch through the epitaxial layer in order to expose the P-body region **503** with the self-aligned contact openings **547**. The polysilicon spacers **542** protect the source region **504** underneath and therefore provide source regions **504** with a

consistent size across the device **500**. In order to provide better ohmic contact with the source metal **517**, a high concentration of P-type dopants may be implanted into the surface of the self-aligned contact openings **547** in order to form ohmic contacts **543**. By way of example, a boron surface implant may be used to form the ohmic contacts **543**.

According to additional aspects of the present disclosure, the device **500** may also have an ESD structured **595**. FIG. 5H' shows that the structure **595** may be formed before the first hardmask layer **556** is removed from the active region. By way of example, the ESD structure may be formed by first depositing an un-doped polysilicon layer over the top surface of the device **500**. A first ESD mask may then be used to selectively dope, with N-type dopants, the regions of the polysilicon that will become the ESD diode **596**. The P-type portions of the ESD diode **596** may be implanted during the P-body implant. A second ESD mask may then be used to selectively remove the polysilicon layer in order to form the ESD diode **596**. An insulative layer **597** may be grown over the ESD diode **596** to protect it from subsequent processing. Thereafter, device **500** may be processed according to the process described by FIG. 5H.

FIG. 6A describes the processing of a device **600'** that is configured for fast switching speeds. The processing of device **600'** is substantially similar to that of device **500** but with an additional step for forming a sub-body layer **688**. The sub-body layer **688** may be formed by implanting a lightly doped P-region below the bottom surface of the body layer **603**. This implantation may occur before or after the P-body layer **603** and/or the source regions **604** are implanted. Thereafter, the processing may continue according to the same processing as device **500**.

FIG. 6B describes the processing of a device **600"**. Device **600"** is processed substantially the same as device **500**, with the exception that there is no source region implanted into the semiconductor substrate **601**. The device may still function because the polysilicon spacer **642** is doped with N-type dopants and may serve as the source region. Thereafter, the processing may continue according to the same processing as device **500**.

Returning to device **500**, the processing continues with standard contact formation procedures. In FIG. 5I a photoresist layer **516** is deposited over the top surface of the device. A gate contact mask may be used to provide an opening through the gate cap over the gate pickup electrode **522**. Additionally, the gate contact mask may provide an opening that allows for the first and second hardmask layers **556**, **555** to be etched through in a non-active area of the device to form a Schottky contact **520**. In FIG. 5J the photoresist layer is removed and the device **500** is prepared for metallization. Source contacts **507** may be formed in the self-aligned contact openings **547**. By way of example, and not by way of limitation, the source contacts may be tungsten. Contacts **520** may also be made to connect the gate pickup electrode to a gate metal **524** and to connect the Schottky metal **525** to the substrate **501**. By way of example, the contacts **520** may be made of tungsten. Finally a metal layer may be deposited over the top surface of the device. The metal layer may then be etched to form a source metal **517**, a gate pickup metal **524** and a Schottky metal **525** connected to the source metal **517** with the use of a metal mask.

Aspects of the present disclosure also describe an additional process for forming a two-step trench oxide layer. First in FIG. 7A an etching process is used to form trenches **770**, **770'** in the substrate **701** through a hard mask having a first insulating layer **756** and a second insulating layer **755**

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formed on a top surface of the semiconductor substrate **701**. Substrate **701** may comprise a heavily doped N<sup>+</sup> drain region **702** and an epitaxial layer **707**. Trenches **770** and trenches **770'** are substantially similar. Trenches **770** may be used for active MOSFET structures, and be located in an active region of the device **700**. Trenches **770'** may be used for gate pickup structures and may be located in non-active regions of the device. As shown, trench **770'** is formed in a P-tub **761**. The trenches **770**, **770'** are formed to a depth  $D_T$  and width  $W_T$ . By way of example, the depth  $D_T$  may be approximately 1.0 micron and the width of the trench  $W_T$  may be between approximately 0.2  $\mu\text{m}$  and 0.5  $\mu\text{m}$ . The trenches may be spaced apart from each other by a mesa that has a width  $W_M$  ranging from approximately 0.2  $\mu\text{m}$ -0.5  $\mu\text{m}$ .

After the trenches **770**, **770'** have been made, an insulation layer **774** may be formed along the walls and the bottom surface of the trench, as shown in FIG. 7B. The insulation layer **774** may have a thickness  $T_2$ . By way of example, and not by way of limitation, the thickness  $T_2$  may be between 400 Å and 1500 Å. Next the trenches **770**, **770'** may be filled with a first portion of the conductive material **709<sub>1</sub>**. The conductive material **709<sub>1</sub>** may be etched back down such that it only fills the lower portion of the trench **772**.

In FIG. 7C the insulation layer **774** in the upper portion of the trench **771** may be etched away. The insulation layer **774** in the lower portion of the trench **772** will be protected from the etching process by the first portion of the conductive material **709<sub>1</sub>**. Then the upper insulation layer **773** may be grown on the walls of the upper portion of the trench **771**. The upper insulation layer **773** may have a thickness  $T_1$ . By way of example, and not by way of limitation, the thickness  $T_1$  may be between approximately 50 Å and 500 Å. Further, it should be noted that even though the approximate ranges of the thicknesses  $T_1$  and  $T_2$  overlap, it is desirable that  $T_2$  should remain larger than  $T_1$ . During the growth of the upper insulation layer **773**, an insulation layer **773'** may also form over the top surface of the first portion of the conductive material **709<sub>1</sub>**. A layer of insulation between portions of the conductive material **709** would cause the gate electrode to have a bottom portion that was not at the gate potential. However, simply etching away the unwanted insulation layer **773'** may damage the upper insulation layer **773**.

Therefore, in FIG. 7D a second portion of conductive material **709<sub>2</sub>** may be used to fill the trench **770**. An anisotropic etching process may then be used to partially remove the second portion of the conductive material **709<sub>2</sub>**, leaving only sidewall spacers that protect the upper insulation layer **773** from subsequent etching processes. Next, the unwanted insulation layer **773'** may be removed with a suitable etching process. Once removed, the remainder of the trench **770** may be filled with a third portion of the conductive material **709<sub>3</sub>**. Thereafter, the processing may continue according to the same processing as device **500**.

While the above is a complete description of the preferred embodiment of the present invention, it is possible to use various alternatives, modifications and equivalents. Therefore, the scope of the present invention should be determined not with reference to the above description but should, instead, be determined with reference to the appended claims, along with their full scope of equivalents. Any feature, whether preferred or not, may be combined with any other feature, whether preferred or not. In the claims that

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follow, the indefinite article "A", or "An" refers to a quantity of one or more of the item following the article, except where expressly stated otherwise. The appended claims are not to be interpreted as including means-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase "means for."

What is claimed is:

1. A MOSFET device, comprising:

a semiconductor substrate of a first conductivity type wherein the substrate includes a lightly doped epitaxial region in a top portion of the substrate;

a body region of a second conductivity type formed in a top portion of the semiconductor substrate, wherein the second conductivity type is opposite the first conductivity type;

a plurality of active device structures formed in trenches in the semiconductor substrate and body region, wherein each active device structure comprises a gate electrode insulated with a gate oxide, wherein an upper portion of the gate oxide is a thickness  $T_1$  and a lower portion of the gate oxide is a thickness  $T_2$ , wherein  $T_2$  is greater than  $T_1$ ; one or more source regions of the first conductivity type formed in a top portion of the body region proximate the gate electrode; an insulative gate cap formed over each gate electrode;

an insulative layer over a top surface of the body region;

a sub-body layer formed below the body region between two or more adjacent active device structures of the plurality, wherein the sub-body layer is a lightly doped region of the second conductivity type, wherein the sub-body layer extends from a depth of the upper portion of the gate oxide to a depth of the lower portion of the gate oxide;

a conductive source metal layer formed over the insulative layer; and

one or more electrical connections that connect the source metal layer with the one or more source regions.

2. The MOSFET device of claim 1, wherein the conductive or semiconductor spacer is a polysilicon spacer.

3. The MOSFET device of claim 2, wherein the polysilicon spacer is doped with dopants of the first conductivity type.

4. The MOSFET device of claim 3, wherein the source region of the first conductivity type is omitted.

5. The MOSFET device of claim 1, wherein each active device of the plurality includes an insulating spacer is formed on sidewalls of the insulative gate cap and a conductive or semiconductor spacer formed on the exposed side walls of the insulating spacer.

6. The MOSFET device of claim 5, wherein the one or more electrical connections are spaced apart from the gate cap by the insulating spacer.

7. The MOSFET device of claim 1, further comprising one or more electrostatic discharge (ESD) protection features.

8. The MOSFET device of claim 1, further comprising one or more a gate pickup trenches.

9. The MOSFET device of claim 1, further comprising a Schottky contact.

10. The MOSFET device of claim 9, wherein the Schottky contact is a body clamp structure.

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